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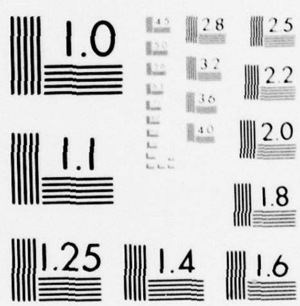
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ADAPTIVE ESTIMATION OF INFORMATION VALUES IN CONTINUOUS DECISION MAKING AND CONTROL OF ADVANCED AIRCRAFT

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This report describes research and development centered on evaluation of information needs in advanced aircraft operations. The selection of information for display is a recurrent, subjective decision involving many factors--aircraft state, environmental conditions, operator capabilities, and acquisition costs, among others. An adaptive computer model has been developed which incorporates these factors into a multi-attribute decision model. The program is designed to capture the operator's information seeking

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policy using a training algorithm based on pattern recognition techniques. The individual policy is then used for information system evaluation and for automated information management.

Experimental tests of the adaptive modeling and information management approaches were made using a task simulation resembling multiple intercept operations in advanced aircraft. Individual subjects (8 in study) navigated a simulated aircraft through a hazardous, changing environment. In doing so, the operators selected from five information sources of varying content, cost, delay and detectability. The information was then used to take one of a number of control actions. Resources were constrained in the task, so that a session terminated when the available costs were exhausted. Two forms of automated information management were used, one based on a multi-attribute utility (MAU) model and one based on a cost-benefit model. Both models were trained adaptively from the manual information selection behavior of each individual. No significant differences in performance score between the two forms of automated information selection were noted, although the MAU model was significantly more cost conserving and accurate in information value analysis. Operator responses to differing levels of information complexity and speed stress were also determined. The report ~~ends with~~ includes an example application of the information management program to F-14 threat intercept operations and ~~with~~ a set of system application guidelines.

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1. INTRODUCTION

1.1 Summary

This report covers the third year of a three-year program of research and development directed toward evaluation of information needs in decision making and control of advanced aircraft. Its purpose is to establish new techniques for the selection of essential information in operational systems. These techniques center on the adaptive modeling of individual decision behavior to derive the immediate value of information. The program is designed to provide the framework for development of operational aids for the real time management of communications. Specific objectives of the three-year program include the following:

(1) Establish a repertoire of techniques to model the information needed for operation of tactical airborne systems.
(2) Provide model-based computer programs capable of ascertaining the potential usefulness of alternative information sources, transmission systems, and information displays.
(3) Develop and experimentally validate a supervisory program for management of communications in simulated tactical airborne systems.
(4) Produce guidelines for field application of the information analysis and management programs in a variety of complex systems.

The initial year's work established techniques for modeling the information seeking decisions necessary for continuous decision making and control of remotely piloted vehicles. The work also experimentally demonstrated the usefulness of adaptive techniques for prediction and analysis of information seeking behavior.

The second year of the program focused on the application of adaptive information model in simulated advanced aircraft operations. The program demonstrated the usefulness of the adaptive decision model for automating the presentation of information and for evaluating the effectiveness of information display configurations. The work reported here, the third year of the program, expands the domain of the information value model to include situations of resource limitations, continued sampling of information, and task loading. The program also involves the incorporation of the multi-attribute decision model into a larger process-oriented model of information management. The work ends with an example application to an operational system, the F-14 AWG-9 weapon system, and with a set of generalized guidelines for application.

1.2 The Problem

Command and control of modern military systems involves selection among increasing large amounts of information. Computerized systems typically make available copious amounts of information concerning remaining resources, environmental state, potential computer aiding, and predicted circumstances and actions. The costs of communications and the limited processing capabilities of the human operator make it necessary to optimize the information selected, transmitted and presented.

The central problem in performing an analysis of information needs is the structuring of the decisions. Choices must be modeled regarding variables such as the mix of information sensing, processing, encoding, transmitting, and display. Throughout this process, a balance must be maintained between maximizing operator awareness of system operation and minimizing communications costs and operator load.

Some initial efforts have been made toward analyzing and automating the communications management functions. Information and control allocation techniques have been proposed using criteria based on queing models (Rouse, 1975; Engstrom and Rouse, 1976; Steeb and Chu, 1978), optimal control models (Sheridan, 1976; Rouse and Gopher, 1977), and multi-attribute decision models (McKendry, Enderwick and Harrison, 1971; Steeb and Freedy, 1976). This program represents an effort to develop, integrate and implement the more promising of these techniques.

1.3 Technical Approach

In brief, the command and control task can be represented as a multi-stage decision task of information acquisition and action selection. The effectiveness of the action decisions are dependent on the appropriateness and timeliness of the information acquired. The choices of what information to transmit thus must reflect the task circumstances, the operator's and automatic system's capabilities, and the communication channel characteristics. These decisions can be expressed analytically using a multi-dimensional set of utilities tied to the potential consequences of the actions. The weights of the various dimensions reflect the importances placed by the individual decision maker on each factor.

A program was developed along these lines, containing both objective probability estimation algorithms and subjective behavioral models. The probability estimation algorithms calculate the likelihood of occurrence of consequences. Such algorithms depend on frequency determinations and optimal Bayesian calculations. The subjective models use these determinations as inputs and are adaptive multi-attribute and cost-benefit forms tied to prediction of behavior. The models demonstrate potential for a number of types of aiding. Among the uses planned are evaluation and specification of communication configurations, individualized training in information acquisition, and automated communications management.

Testing of the models was accomplished by determining the aiding and analysis capabilities provided in an advanced aircraft task simulation. The task simulation incorporates many of the functions involved in multiple intercept operations and has extensive performance analysis capabilities.

1.4 Current Objectives

The focus of this phase of the research and development program is to extend the application of the adaptive decision model to include information evaluation and management functions in an advanced aircraft context. This builds on the findings of the first and second year's work in which the adaptive program was found to be a useful model for analyzing and predicting information seeking behavior, for aiding the information choices, and for evaluating the usefulness of alternative information system configurations. The specific objectives of this third-year program include:

(1) Expand the domain of the information value model to include situations of resource allocation and continued sampling of information.

(2) Incorporate the information value model into a process model of information management: analytically relate information sources to attributes, attributes to decisions, and decisions to users.

(3) Expand the task simulation to include limited resources and operator loading. Ascertain unloading provided by automated information management based on multi-attribute utility (MAU) and cost-benefit models.

(4) Produce guidelines for decision model choice, model structuring, and estimation techniques; and describe methods of application to information system evaluation and management.

1.5 Applications

Model-based aiding for information value selection appears to be most applicable to decision tasks which feature some or all of the following operational characteristics:

(1) High Information Load. The operator is in a time-stressed decision task. For each decision he can process only a portion of the available data set and must choose an action within a short time.

(2) Costly Information Transmission. The transmission of data to the operator is subject to cost, risk of detection, or limited transmission capabilities. Immediately valuable information must be selected.

(3) Significant Judgmental Factors. The decision maker must consider the credibility and content of the evidence along with the probabilities and utilities of the consequences associated with each ensuing action.

Among the examples of actual military and civilian decision-making situations which require such tasks are:

(1) Advanced aircraft decision making and control.

(2) Remotely piloted vehicle guidance.

(3) Satellite intelligence transmission.

(4) Supervision of air, ground, or sea support operations.

(5) Crime information management.

(6) Coordination of remote sensing of the environment.

1.6 Report Organization

The organization of this report is as follows: Chapter 2 reviews selected background concepts, traces the development of the adaptive models, and describes previous experimental studies performed under this program. Chapter 3 discusses the expansion of information value modeling to situations of limited resources, varying operator loading and continued sampling of information. Chapter 4 describes the experimental plans and procedures for testing the usefulness of the adaptive MAU and cost-benefit models. Chapter 5 summarizes the results of the experimental study. Chapter 6 presents a discussion of the research findings and opportunities for application. Chapter 7 discusses use of the model in an operational setting: flight officer aiding in the F-14 aircraft. The report ends with system application guidelines summarizing the findings of the three years of work.

2. INFORMATION VALUE MODELING IN ADVANCED AIRCRAFT OPERATIONS

2.1 Overview

The selection, acquisition and processing of information are activities that are involved in virtually every aspect of tactical airborne operations. The operator must continuously maintain an awareness of the aircraft state, the environment, the capacity and quality of the communication channels, and the progress toward objectives. The operator must, under considerable time stress, weigh the probable usefulness and costs of a variety of competing forms of information--mission status, track data, environmental information, aerodynamic functioning, etc. These moment-to-moment judgments must often be based on subjective factors, since the decision is normally too complex and dynamic to be analytically tractable.

Adaptive decision models based on multi-attribute utility analysis have been employed in earlier studies (Steeb, Chen and Freedy, 1977; Steeb, Davis, Alperovitch and Freedy, 1978) to model the information seeking decisions. These techniques were found to hold a great deal of promise for aiding in advanced aircraft operations. Tactical airborne systems typically require consideration of voluminous amounts of relevant and irrelevant information. At the same time, severe time stresses and interfering tasks can degrade the information integration processes. To reduce the operator load, combat aircraft typically have sophisticated autopilot and weapon control systems. These systems have been shown to be extendable to include functions of information evaluation and management, since they take into account the key factors of environmental state, vehicle state, and task objectives. The following sections describe the initial definition, structuring, and implementation of adaptive decision models in the context of tactical airborne operations.

2.2 Information System Characteristics

The typical advanced aircraft mission can be defined by a series of mission phases, much like the stages of the RPV supervision task analyzed in the initial year (Steeb, Chen and Freedy, 1977). The phases can be characterized by the danger or frequency of threats, the time available for decision making, and the options and characteristics of information concerning the aircraft and the environment.

The information available at a given time is dependent on the environmental situation, the sensor characteristics, the data base content, and the display capabilities. The information itself may consist of data regarding weather conditions, aerodynamic status, target track, ECM, and mission status.

The costs of acquiring information result from the sensor characteristics, the direct and indirect costs of sensor deployment, information processing and display, and the amount of attention the operator can contribute. The direct costs of information acquisition include such factors as energy expenditures and equipment expenses. Indirect costs include increased possibilities of detection and countermeasures. The available operator attention, finally, is defined by the task demands and the individual capabilities of the operators.

The costs and payoffs associated with the various possible outcomes vary with mission phase. The consequences are defined not only in terms of attrition of equipment and attainment of objectives, but also as a function of organizational policy and procedures. The relative importance of fuel expenditures, vehicle survival, countermeasures, etc., change as the mission objective is approached, attained, or past. The relative importance of these factors must be assigned by the human operator or by the command group.

Available time for decision making varies throughout the mission as a direct function of the varying vehicle speed, altitude, and surrounding weather conditions. Altitude, cloud cover and ECM determine the distance that obstacles, navigation points, or targets can be observed. The speed then determines the available time. Decision time can be expected to influence the amount of information that can be processed and the probability distribution of the possible consequences.

The pilot as the airborne system manager faces a variety of information sources and displays--such as Master Monitor Display, Integrated Multi-Function Display, etc. The pilot has the responsibility to monitor the aircraft subsystems as well as supervise the autopilot and to detect possible hardware failures and potential hazards. He must constantly respond to action-evoking events such as: communication of information, change of aircraft configuration, and reduction of 4-D guidance errors. Finally, the pilot is required to respond to unexpected events such as identification and avoidance of threats, change of flight plan, establishment of the backup mode, and declaration of emergencies, etc. The pilot is in a multi-information selection situation.

In sum, the selection of information and control to allocate to the supervisory human operator is a complex and dynamic decision. The decision maker must continually weight the probable usefulness of the information against the costs of acquiring it. Since this decision is especially difficult, the costs and benefits are both multi-dimensional and probabilistic.

2.3 Structure of the Information Seeking Models

2.3.1 The Multi-Attribute Models. Multi-attribute utility (MAU) models, pioneered by Raiffa and his colleagues (Raiffa, 1969; Keeney and Raiffa, 1975) and by V. Winterfeldt (1975) provide a framework for aiding the

information management process. These utility models tie the information decisions directly to the ensuing action decisions. The value of obtaining information is determined by calculating its impact on the expected utility of the subsequent action decision. The information is assumed to change the probability distributions of the consequence sets and, in turn, to revise the expected values of the alternative actions. Nevertheless, the form of the model is again a linear additive rule. The utility of an action is considered to be an aggregate of many possible outcomes, each expressed along a set of attributes:

$$EU\ (a_k) = \sum_{\substack{\text{states} \\ h}} P(z_h) \sum_{\substack{\text{attributes} \\ i}} U_i\ (a_k, z_h) \tag{2-1}$$

Where EU (a_k) is the expected utility of action k, $P(z_h)$ is the probability of state z_h occurring, and $U_i\ (a_k, z_h)$ is the utility function over the i^{th} attribute associated with state h and action k. The formulation is the result of several key simplifying assumptions. The decision maker is assumed to be risk neutral, so that he is indifferent between the expectation across a set of uncertain outcomes and the uncertain outcomes themselves. This allows the probabilities to be entered as simple coefficients. Also, the attributes are assumed to satisfy additive independence, allowing the linear additive form of aggregation. Tests for compliance with these assumptions can be found in V. Winterfeldt (1975) or Keeney and Raiffa (1976).

The impact of a message or item of data is to change the probability distribution of the states z_h. Once the message is received, a maximum utility action $a^*(y)$ can be identified. The expected utility of selecting an information source S then becomes (Emery, 1969):

$$EU\ (S) = \sum_{\substack{\text{messages} \\ y}} \sum_{\substack{\text{states} \\ z}} P(z_h)\ P(y|z_h)\ u(a^*(y), z_h) \tag{2-2}$$

Here $u(a^*(y), z_h)$ is the utility of taking action $a^*(y)$ given that state z_h occurs. The utility function is again multi-attributed, but for simplicity $u(a^*(y), z_h)$ is portrayed as having already been aggregated across the various dimensions.

This type of analysis, championed by such researchers as Emery (1969), Marshak (1971) and Wendt (1969), is suited for highly structured tasks. Not only must the possible states, messages, actions, and outcomes be specifiable, but the prior state probabilities and the conditional probabilities characterizing the information system must be derivable. The sequence of decision stages can be depicted using a decision tree, as shown in Figure 2-1. The tree is folded back by associating with each possible message the maximum expected utility of the subsequent actions. This folding back represents graphically the process of EU maximization. The favored information source S is then identified by comparing the expectations taken over all possible messages.

2.3.2 <u>Other Methodologies</u>. A number of other techniques have also been proposed to model information seeking behavior. Among these are information theory models, (Whittemore and Yovits, 1973), optimal control formulations, (Sheridan, 1976; Rouse and Gopher, 1977), queing models, (Rouse, 1975; Engstrom and Rouse, 1976) and information integration techniques (Anderson and Shanteau, 1970). For the most part, these techniques demand rigid problem structuring and continuous variables. More often, the communication decision is incompletely defined and involves choices among discrete rather than continuous alternatives. Thus the discrete operators used in cue regression and multi-attribute utility models--matrices, difference operators, and detailed parameter enumerators--may be more appropriate. The interested reader is directed to the initial technical report (Steeb, Chen and Freedy, 1977) for a more detailed examination of these approaches.

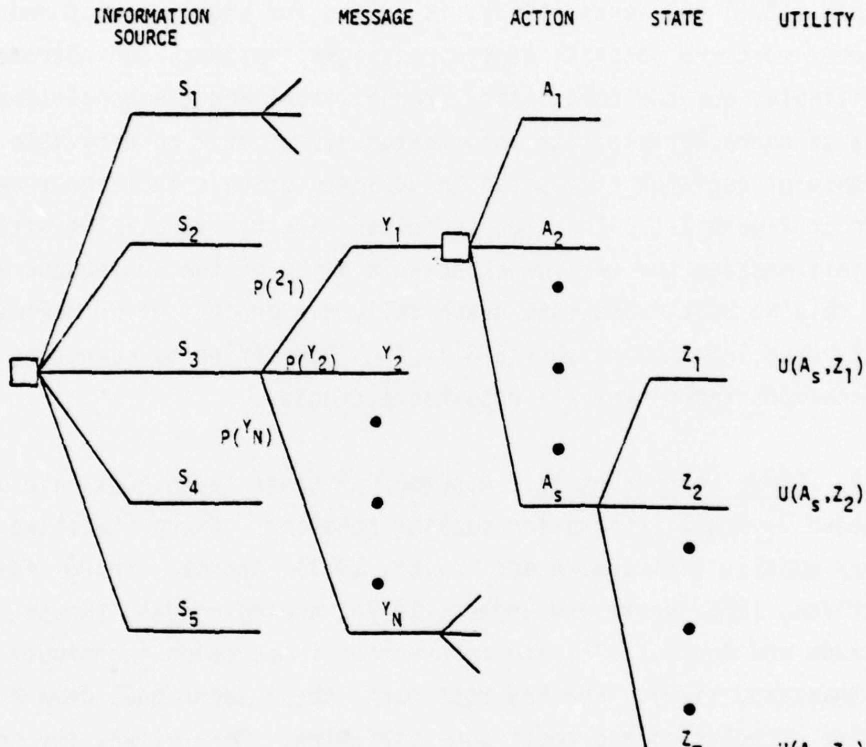


FIGURE 2-1.
DECISION TREE FOR INFORMATION SEEKING

2.3.3 <u>Information Management Functions</u>. The major information management functions faced by the operator are diagramed schematically in Figure 2-2. The information available consists of data regarding the aircraft, the targets, the environment, and operator and system capabilities. The information is then used by the operator to perform supervisory control actions.

The information and control choice sequence is that diagramed with the decision tree of Figure 2-1. This diagram is repeated with labels representative of tactical airborne operators in Figure 2-3. The multi-attribute utility formulation provides a useful basis for structuring both the information and control decisions. The specific steps of the modeling process are outlined in Figure 2-4. The figure shows the two sides of the modeling problem, probability estimation and utility assessment. The upper portion of the figure details the processes of probability estimation. These include delineation of the possible states of the environment, evaluating the current level of uncertainty concerning states, selecting information to reduce the uncertainty, and revising the probability estimates in light of the new data. The lower portion of the figure is concerned with outcome evaluation or utility estimation. Here the levels and importance weights for each dimension of consequence are determined.

The key element in the probability estimation sequence is the information acquisition stage (enclosed by dotted lines). Figure 2-5 elaborates this stage, showing the steps that go into the choice of information and the subsequent incorporation of the datum into the situation estimate. The upper portion of the figure deals with the information source selection. The characteristics of the various available sources are determined by observation and analysis. This estimation of the characteristics of the information sources is accomplished by successive comparisons of messages received and subsequently observed states. The choice of information source

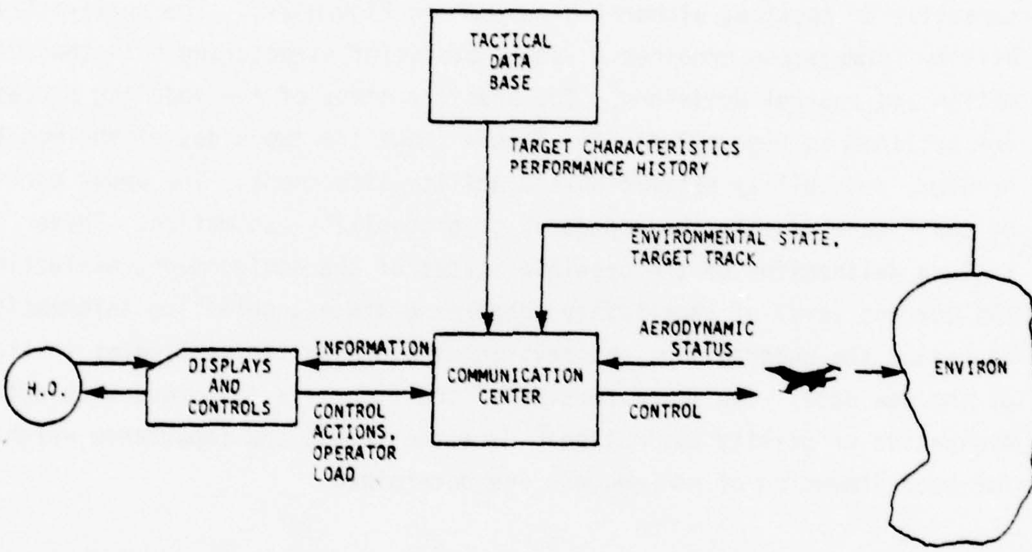


FIGURE 2-2.
MAJOR INFORMATION MANAGEMENT FUNCTIONS

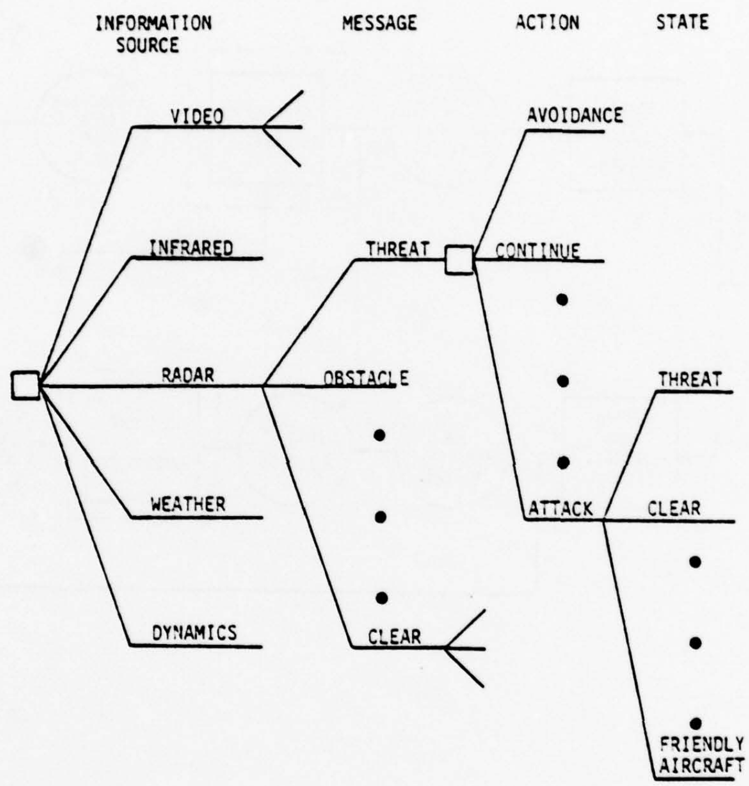


FIGURE 2-3.
DECISION TREE FOR INFORMATION SEEKING
IN TACTICAL AIRBORNE OPERATIONS

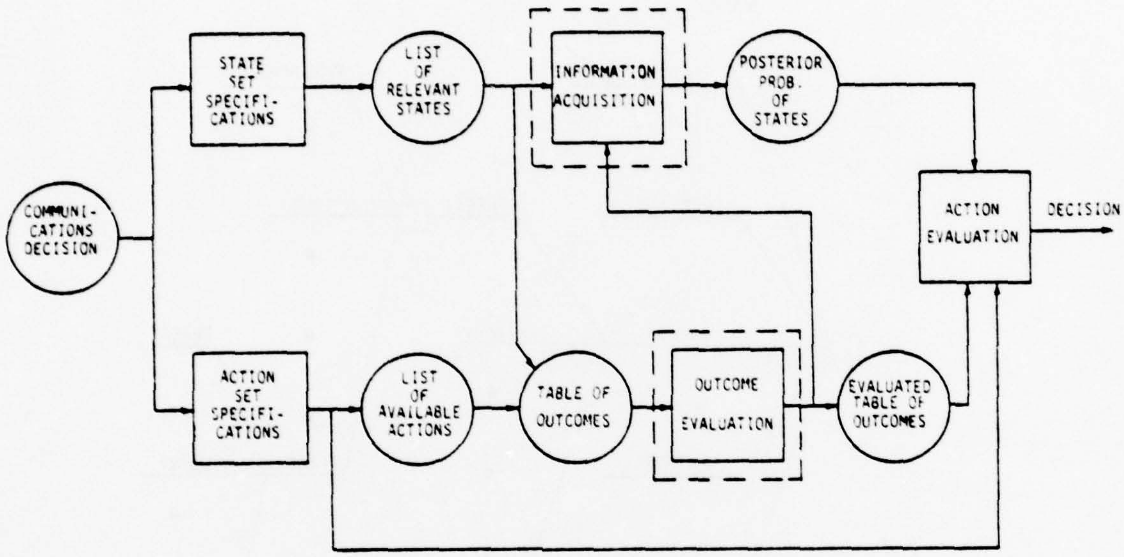
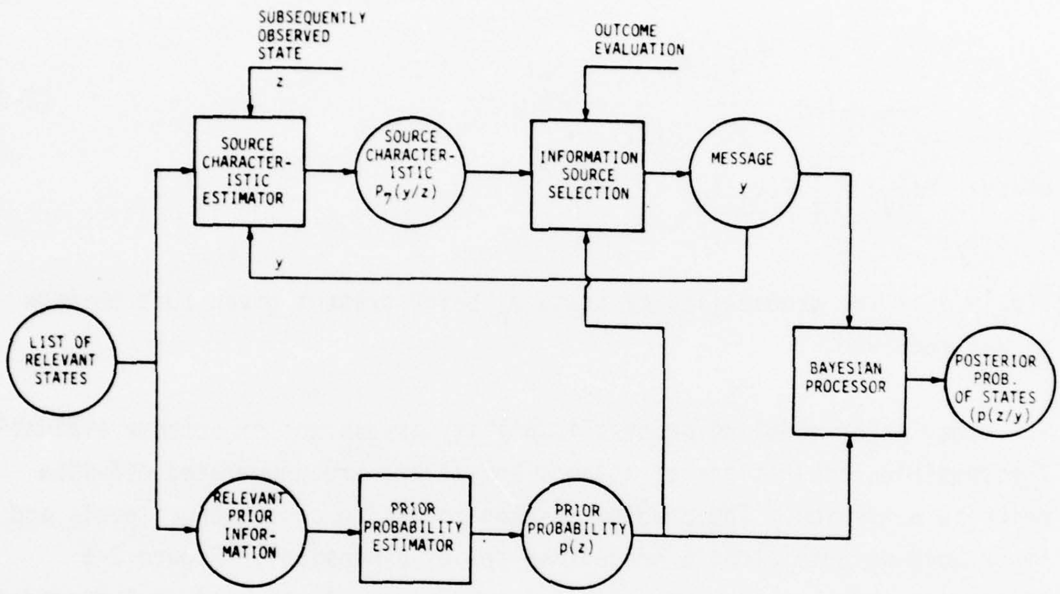


FIGURE 2-4.
DECISION PROCESS CHART



(This is an elaboration of the "Information Acquisition" block of Figure 2-4)

FIGURE 2-5.
PROCESSES INVOLVED IN PROBABILITY ESTIMATION

is then made according to the potential impact of the information on the prior probability estimate. Once a source is selected and a datum observed, the information is incorporated into a revised situation estimate through Bayes' rule:

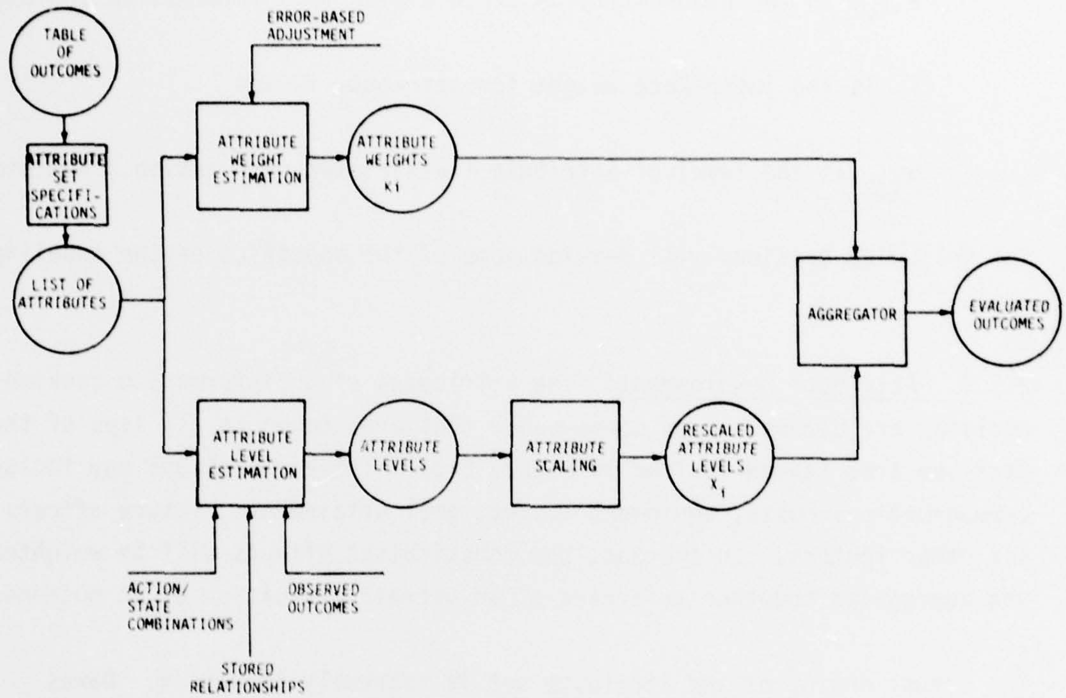
$$P(z_h|y_j) = \frac{P(y_j|z_h) \cdot P(z_h)}{(P(y_j)} \qquad (2\text{-}3)$$

where $P(y_j) = \sum_i P(y_j|z_h) \cdot P(z_h)$

$P(z_h|y_j)$ is the probability of state z_h being present given that message y_j was received.

The other major modeling process is utility assessment or outcome evaluation. The possible combinations of actions and states are enumerated off-line prior to a mission. The problem is then to assign consequence levels and importance weights along a predefined set of dimensions. Figure 2-6 elaborates this process. The first step is the selection of an independent, exhaustive, and predictive attribute set. The attributes are the various constituent aspects of the consequences. Each combination of information, action and outcome is associated with a set of attribute levels. This is done by observation and adjustment, just as in the determination of information source characteristics. Scaling procedures are applied to the raw consequence dimensions to arrive at normalized values. Each attribute is scaled so that its plausible range spans zero to one. These processes result in a specification of the parameters of the basic multi-attribute formulation:

$$E\,[u(x)]_s = \sum_{k=1}^{M} P(z_k) \sum_{i=1}^{N} K_i \; u_k \; (x_{ijk}) \qquad (2\text{-}4)$$



(This is an elaboration of the "Outcome Evaluation" block of Figure 2-4)

FIGURE 2-6.
PROCESSES INVOLVED IN OUTCOME EVALUATION

where

$E\,[u(x)]_s$ is the expected utility of information choice s,

$P(z_k)$ is the probability of state k with this information choice,

K_i is the importance weight for attribute i, and

x_{ijk} is the level of attribute i associated with action j and state k.

The following sections will develop some of the specifics of the modeling cycle.

2.3.4 Attribute Development. The attributes of an information seeking decision are dimensions of consequence that are common to all tips of the decision tree (shown earlier in Figure 2-1). These dimensions may include communications costs, equipment losses, goal attainments, future effects, and other factors. In the end, the constitutent effects will be weighted and aggregated together to arrive at an overall evaluation of an outcome.

The actual choice of the attribute set is extremely important. Dawes (1975) states that the choice of factors to include is probably of greater impact than the determination of the model form. Desirable characteristics are accessibility for measurement, independence, monotonicity with preference, completeness of the set, and meaningfulness for feedback. Monotonicity, in this content, implies that an increase in the attribute level always results in an increase in preference. If the attribute levels are monotonic, a simplification is possible. Fisher (1972) and Gardiner (1974) note that a straight line approximation to the utility function results in minor losses of model accuracy. The estimated utility (ignoring uncertainty for now) is then a weighted linear combination of attribute levels:

$$U(a_z, z_h) = \sum_i k_i x_{ihk} \tag{2-5}$$

where $U(a_z, z_h)$ is the utility of state h occurring with action z, k_i is the importance weight for attribute i, and x_{ihk} is the level of attribute i associated with state h and action k.

Information costs may comprise attributes of special note. Often, the benefits of an information acquisition are simply weighted against the costs of acquiring the information. If a net gain is anticipated, acquisition of the information is considered justified. Often, though, the costs themselves are multidimensional, comprising energy costs, time delays, equipment expenditures, and risks of detection. The scaling, weighting, and aggregating of these costs may be most easily performed in combination with all of the non-cost attributes--tactical gains, political impact, etc. Then, trade-offs among each of the factors may be performed in a single, consistent operation.

A candidate set of attributes might contain factors from five areas:

(1) Communications Costs. The expenditures associated with use of the information sources. These may include requirements of energy, equipment, and operator attention.

(2) Equipment Attrition. Consequences concerning the integrity of the vehicle. Included are fuel expenditures, system damage, and vehicle loss.

(3) Objective Attainment. The degree of accomplishment of the mission objectives. Target goals may be the area reconnoitered, adversaries dispatched, and political impact obtained.

(4) Dynamic Effects. The future consequences resulting from the current actions. These consequences may include effects on subsequent action choices, availability of future information, and changes in the environment resulting from the action.

(5) Subjective Needs. The operator may have propensities for obtaining (or refusing) information beyond that called for by the above factors. These preferences reflect the needs of task continuity, maintenance of load, or other idiosyncratic factors.

A useful consequence set might contain a single dimension or attribute from each of these categories. In fact, five attributes appears to be an upper limit to the number of factors a decision maker can effectively consider (V. Winterfeldt, 1975). If several factors contribute to one consequence dimension, these factors should be combined using a single common scale--dollars, ship-equivalents, fuel quantity, etc.

Each of the attributes--communications costs, vehicle losses, etc.,--must be scaled with interval properties along a set range. The least desirable consequence that may occur is assigned a level of zero on the scale. The most desirable consequence is assigned a level of one. The weighting factors k_i should also be normalized so that the overall worst combination of factors results in a value of zero and the overall best combination a value of one.

A special situation occurs with probabilistic attributes. Assuming risk neutrality, probabilistic consequences may be computed according to their expected level. For example, the vehicle loss attribute may have three possible levels, each with a different probability of occurrence. The expected value is computed by the following additive expression:

$$E(x_{ij}) = \sum_{k=1}^{3} P(z_k)x_{ijk} \tag{2-6}$$

where the parameters are defined as in Equation 2-4. Once the attributes are defined and their levels are determined, the aggregation rule must be identified. The attributes--costs, losses, delays, future impacts, etc.,--may combine in an additive, multiplicative, or more complex fashion (see Keeney and Raiffa, 1975, for a description of some of the more popular formulations). For the work here, the simple additive form, exemplified by Equation 2-5 appears to be the most suitable. The additive form is robust, intuitively easy to understand, and simple. Also, the linear form of the additive will be seen to be amenable to estimation by pattern recognition techniques.

2.3.5 Consequence Level Determination. The actual level of each of the attributes for a given outcome can be determined by mappings between predictive features and the attributes. Predictive features must be identified which are accessible to an onboard program and capable of determining the consequence levels. Mappings between the predictive features and the attributes are either pre-established or determined by observation and adjustment.

The data available to the decision program are:

(1) Directly-sensed information concerning the environmental state (weather, terrain, ECM, target track).
(2) The vehicle state (velocity, fuel, autopilot capability).
(3) The information system characteristics (capacity, noice, cost).
(4) Tactical data (technical characteristics of own and enemy aircraft, sensors and weapons; information about the operations area).
(5) Action alternatives (control responses, weapon deployment).
(6) Operator capabilities (attention, load).

A manageable subject of these features must be determined. The consequence mapping can then be refined by comparison of the predicted and actually observed consequences. The mapping can be developed either by prior definition, by regression, or by the pattern recognition techniques described in the coming section.

2.3.6 Attribute Weight Estimation. The policy defining factors in the model, the importance weights k_i, are parameters suitable for either objective or subjective estimation. If the consequences can be defined along objective scales (dollars, ship-equivalents, etc.), then the weights could be derived by analysis and input prior to system operation. Unfortunately, Felson (1975) states that only in a few highly structured situations can such an optimal model be derived. More often, the operator's goal structure, expressed as importance weights, must be elicited or inferred and then incorporated in the model. There are a number of advantages to such subjective estimation, particularly with respect to allocation of function. By incorporating individualized operator weights in the model, the complex evaluation and goal direction functions remain the responsibility of the operator, while the normative aggregation functions are assumed by the computer. Also, operator acceptance of aiding by the model may be increased since his preferences are incorporated in the machine decisions.

The operator's subjective weights may be defined off-line by elicitation or on-line through inference. The off-line methods include direct elicitation of preference, decomposition of complex gambles into hypothetical lotteries, and use of multi-variate methods to analyze binary preference expressions. These techniques are accurate and reliable in many circumstances, but they have a number of disadvantages when applied to operational systems. Typically, these methods require two separate stages--assessment and application. Assessment requires an interruption of the task and elicitation of responses to hypothetical choices. Problems arise with such

procedures since the operator's judgments may not transfer to the actual situation; the decision maker may not be able to accurately verbalize his preference structure (Macrimmon and Taylor, 1972); and the judgments made in multi-dimensional choices are typically responses to non-generalizable extreme values (Keeney and Sicherman, 1975).

Estimation techniques relying on inference from in-task behavior may be more useful. The inference techniques can be based on non-parametric forms of pattern recognition. Here a model of decision behavior is assumed and the parameters of the model are then fitted by observation and adjustment. Briefly, the technique considers the decision maker to respond to the characteristics of the various alternatives as patterns, classifying them according to preference. A linear discriminant function is used to predict the decision maker's choices, and when amiss, is adjusted using error-correcting procedures. In this way, no preference ratings or complex hypothetical judgments are required of the operator.

The adaptive nature of the estimation program is shown in Figure 2-7. Expected consequence vectors associated with each information source are input to the model. These consequence vectors are dotted with the weight vector, resulting in evaluations along a single utility scale. The maximum utility choice is determined and compared with the operator's actual choice. If a discrepancy occurs, the weight vector is adjusted according to the following rule:

$$\underline{k}' = \underline{k} + \lambda(\underline{x}_c - \underline{x}_m) \tag{2-7}$$

where $\underline{k}'$ is the updated weight vector

$\underline{k}$ is the previous weight vector

λ is an adjustment constant

$\underline{x}_c$ is the attribute vector of the chosen alternative

$\underline{x}_m$ is the mean attribute vector of all alternatives ranked by the model above the chosen alternative.

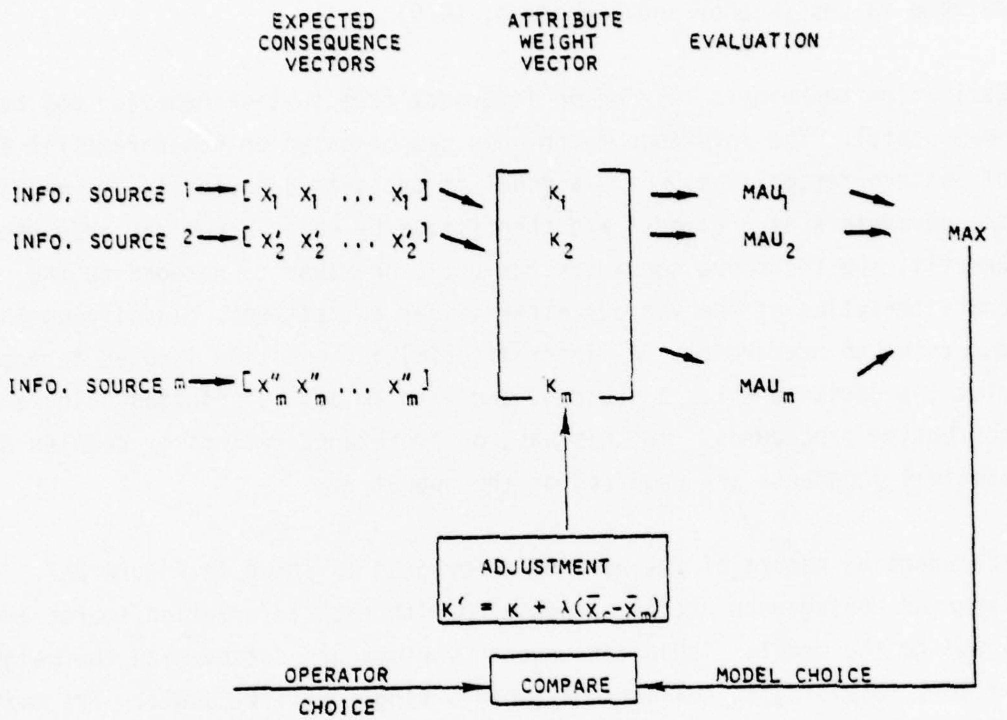


FIGURE 2-7.
ADAPTIVE ESTIMATION PROCESS

Ideally, the error correction moves the weight vector in a direction minimizing subsequent errors. The amount of movement depends on λ, the adjustment increment. Nilsson, 1965, describes several different forms of λ that can be used depending on the combination of speed and smoothing desired.

The type of criteria used for model training is also a major consideration. The training may be based on objective outcomes such as stock market consequences, or subjective criteria such as actual operator decisions, or on some combination of subjective and objective criteria. The approach based on both objective and subjective criteria is the most involved. In many situations, an occasional indicator of objective performance is observable. The aircraft may be lost, the target attained, or some number of subgoals accomplished. In this way, the correctness of a sequence of actions may become objectively known. The utility model would be trained subjectively prior to this by observation of the operator's choices. If the sequence of choices led to an objectively favorable outcome, the trained parameter set would be retained. If the outcome was unfavorable, the parameter set would be returned to the levels present prior to the sequence of decisions. In this way, objective criteria would guide overall training, but the explicit decision-by-decision policy for information management would be subjectively derived.

Of course, the adaptive techniques of estimation described above are warranted only if repetitive decisions are available for training and if the differential weighting of attributes is important. In cases where only a few non-repetitive decisions will be made, off-line estimates of the weights k_i are favored. Here, techniques such as direct estimates, hypothetical lotteries, or multiple regression are used for estimation prior to the mission. It is assumed with these techniques that the system requirements will not change after the estimates.

Questions concerning the importance of differential weighting are more basic. Unit weighting schemes (in which all weights k_i are set equal to 1.0) have been found to be quite effective in certain circumstances. Errors in the model form, positive correlations between variables, and small sample sizes all reduce the predictive capabilities of differential weights compared to unit weight (Einhorn and Hogarth, 1975). Essentially, the more precise and parsimonious the model, the more important differential weights are.

Unit weighting schemes are expected to see only minor application in aiding advanced aircraft operations. Careful selection of attributes minimizes intercorrelations between variables, and the correlations that do occur should tend to be negative. For example, in most cases costly information is generally more informative than inexpensive information, and equipment attrition tends to be negatively correlated with goal attainment. These circumstances favor inferred weight models. Unit weighting schemes should primarily be useful as starting points for estimation, or as strategies for situations in which a great deal of noise is present.

2.3.7 Probability Estimation. The major probability parameters requiring estimation are the prior probabilities $P(z)$ and the conditional probabilities $P(y|z)$. The priors are the probabilities of state z in a particular situation. The conditional probabilities deal with the likelihood of receipt of message y if state z is present. Both of these forms of probabilities can be estimated from frequency counts.

A second area of uncertainty concerns the consequence levels associated with a given message and state. These are the performance probabilities and are derived from stored data: detection range, target hardness, personnel performance, system reliability, guidance system accuracy, etc. The probability of outcome given the message received can be computed for each

set of actions. Comparison of the messages received, actions taken and the consequences subsequently observed provide the necessary data.

2.3.8 Level of Detail. The level of detail handled by the model is basically a problem of efficiency of categorization. Choices of the fineness of distinction of information modes, messages, and states involves a trade-off of the model complexity (and processing time) against degree of specification of aiding. For example, the information available may be classified by content element (threat identify, weather formation, malfunction location, terrain characteristics, etc.) or by source (radar, infra-red sensor, video, tactical data base, radio, etc.). Similarly, the messages and states may be represented in the model as specific details of threat position, course, speed and identification, or more globally as specific threat presence or absence. Of course, separate prior and conditional probability estimates must be maintained for each state represented in the model.

Much of the question of level of detail was to do with the concept of payoff relevance, a term introduced by Marschak (1963). The partitioning of the information space must result in differences in (1) the existing representation of the decision situation, (2) the actual decisions made, and (3) the utility resulting from the changed decisions. Information may be ineffective in changing the situational representation and resulting decisions because the data is too coarse or too fine. Information that is too coarse fails to distinguish between effectively different states of nature for at least one of the alternative actions. Information that is too fine differentiates between states having identifical payoffs for all actions. Effective information--data that is not too fine or too coarse--is termed by Marschak to be payoff relevant. In the experimental application of the model, attempts were made to structure the model so that the cost of the chosen level of detail is commensurate with the benefits.

2.4 Aiding in Advanced Aircraft Operations

2.4.1 Forms of Aiding. It was noted earlier that three major forms of aiding are possible once the operator's decision policy is estimated: (1) system evaluation and design, (2) automated management of information, and (3) operator training. This section will describe in more detail the potential of model-based aiding for tactical airborne systems. Recounting briefly, system evaluation and design entails the determination of each system component's contribution to information value (satisfaction of operator needs). Specification of system configuration commensurate with task demands and individual operator needs is then possible. Automated management of information is the moment-by-moment control of display content and format by selection among available information. Operator training, finally, involves the use of policy feedback to train the operator to make effective information and control decisions. The first two of these uses of the decision model, system evaluation and automated information management, will be described in greater detail in the following sections. Model-based training is presently outside the scope of this work.

2.4.2 System Evaluation. Two types of evaluation are possible using the information extracted from the information value model: direct contribution and marginal contribution. Each of these evaluation measures is described below.

Direct Contribution. This is the user-specific value of a given information source in a given task situation. As such, it is a simple aggregation of components, weighted by the user's policy:

$$\text{info value}_{jks} = \sum_{\substack{\text{attributes} \\ i}} k_{ij} \, \bar{x}_{ik} \qquad (2\text{-}8)$$

where info value $_{jks}$ is the aggregate value of source s to user j in situation k, k_{ij} is the importance weight of attribute i to user j; and $\bar{x}_{ij}$ is the mean level of attribute i in situation k. This formulation is useful when each information source contributes to a different task--threat detection, navigation, etc. The direct contribution measure does not deal with information sources having overlapping function.

Marginal Contribution. In a group of information sources with overlapping function, the information value of one source can be calculated with the following expression:

$$\text{information value}_{jks} = \sum_{\substack{\text{attributes} \\ i}} k_{ij} x_{ik} - \max_{\substack{\text{over} \\ \text{remaining} \\ \text{sources}}} \sum_{i} k_{ij} x_{ik} \tag{2-9}$$

This is the incremental value of a source over the next most highly valued source. The summation of all positive contributions for a given source indicate the source's value in the particular task situation.

Using either the direct or marginal measure of information value, the mission value of an information source can be calculated as the summation across the probability distribution of task situations.

$$\text{info value}_{js} = \sum_{k} \text{prob (situation k)} \cdot \text{information value}_{jks} \tag{2-10}$$

This provides an overall, user-specific index of information value.

2.4.3 Automated Management of Information. The information value model described in section 2.3 can be used directly for management of information. The multi-attribute utility model represents the policy of the specific user, it has access to the factors characterizing each information choice,

and it can be linked to the onboard information control system. The model can thus be configured to automatically scan the available information sources, select the immediately most useful source, and display it to the operator. The following sections describe the initial experimental applications of these aiding programs.

2.5 Experimental Validation

Evidence for the usefulness of the multi-attribute utility formulation and adaptive estimation programs was obtained during the initial year of the program (Steeb, Chen and Freedy, 1977). A simulation resembling control of a remotely piloted vehicle (RPV) was used in this study. Individual subjects navigated the RPV through a changing hazardous environment. In doing so, the operators selected different combinations of information and control allocation. The adaptive model was found to be significantly more predictive of subject's behavior than either a constant, unity weight model or an off-line method of weight estimation. Also, the model was found to be useful in identifying different decision policies or styles.

Use of the adaptive and off-line models to make choice recommendations to the operators had mixed results. The differences in task performance noted between the recommendation-aided and unaided conditions did not reach significance, although those who followed the recommendations most closely achieved the highest scores. Also, the adaptive model was found to be useful in identifying strategies which led to superior performance.

The second year effort (Steeb, Davis, Alperovitch and Freedy, 1978) built on the findings of the initial work by investigating the usefulness of the information value models for automating the presentation of information and for evaluating the effectiveness of information display configurations. The program also re-directed the application area from one of remotely

piloted vehicle supervision to one of information selection in advanced aircraft. A simulation based on multiple threat intercept operations in advanced aircraft was developed. Additional factors for time stress and an expanded information and action set were included in the new decision model.

The primary focus of this second series of experiments was to test the effectiveness of the adaptive decision model for information management and information system evaluation. Subjects (12 in the study) were required to select from a variety of forms of information regarding multiple, uncertain threats and to take aggressive or avoidance actions in response. The information options differed in cost, time delays, threat discrimination and enemy detection. The operators experienced a sequence of decisions organized into mission phases. Comparisons were made between (1) automated information management based on the adaptive model described earlier, (2) automated information management based on information seeking strategies elicited directly from the operator, and (3) manual information selection. Each subject experienced sessions of each of these conditions under low and high speed stress. Information management using either automated form was found to result in improved task performance over manual selection. The improvement with aiding was enhanced in situations of high-speed stress. The performance score improvement with adaptively-based management over manual selection changed from 30 percent improvement in the low-speed stress conditions to 60 percent improvement in the high-speed stress conditions. Finally, the adaptive technique was found to be superior to direct policy elicitation, both for automated information management and as a basis for information system evaluation.

The following sections extend these results both experimentally and analytically to the more complex and realistic situations of limited resources, continued sampling of information, and variable operator loading. Also, the full process of information acquisition, processing, formating and display will be considered.

3. EXPANDED SYSTEM DEVELOPMENT

The preceding sections have described how an adaptive computer program organized around a multi-attribute decision model can be used for modeling and even automating the information selection processes. Up to this point, the model has by necessity been developed in a relatively simple context. While the analysis has addressed problems of multiple criteria, probabilistic consequences and time-varying behavior, a variety of other factors must be considered. For example, the emphasis has been on the choice of information for transmission and presentation. It is necessary to expand the domain of the information evaluation methodology to explicitly represent the complete sequence of sensor selection and adjustment, data encoding and transmission, and information processing and display. Also, the influences on model performance of operator loading, continued sampling of information, and limited resources have not been determined. These important questions will be dealt with analytically in the following sections. Experimental studies of the effects of limited resources and operator loading on the information value models will be described in the coming chapter.

3.1 Limited Resources and the Use of Cost-Benefit Decision Criteria

Tactical Airborne Operations are often subject to constraints on certain resources. Fuel, weapon stores, and time aloft may be constrained by absolute limitations. The previously described linear additive MAU formulation treats each of these factors as additive dimensions of value. For effective operation, however, the flight officer would be expected to choose actions which maximize the benefits per cost expended until the resource is exhausted. This process is exactly that of cost-benefit analysis. Here the benefit-to-cost ratios $u(x)/c$ are calculated for each alternative, and the actions with the highest ratios

are chosen (Edwards and Guttentag, 1975; Fischoff, 1977). For ratio scale properties to hold, benefits must be calculated with respect to a zero cost option.

The resulting information selection criterion is somewhat more complex than the additive MAU formulation. The benefit/cost ratio of a given alternative is:

$$\text{Benefit/Cost ratio (option}_k) = \frac{\sum_i k_i A_{ik}}{\sum_\ell k_\ell C_{\ell k}} \qquad (3\text{-}1)$$

Where k_i is the importance weight of (benefit) attribute i, A_{ik} is the level of attribute i associated with option k, k_ℓ is the importance weight of (cost) attribute ℓ, and $C_{\ell k}$ is the level of attribute ℓ associated with option k.

The cost-benefit formulation is amenable to adaptive estimation in the same manner as the additive MAU criterion of equation 2-4. The attribute levels divided by the option cost (A_{ik}/C_k) replace the A_i in Figure 2-7. The comparison of recommended and actually chosen options takes place as before. However, a modification of the adjustment rule is necessary, since the adjustment procedure does not produce a change in the importance of cost. In fact, if two options differ widely in cost, the chances are that the lower cost option will be chosen regardless of other variables. The adjustment would then have only a 50 per cent change of moving in the correct direction. The highest probability of correct adjustment would occur when the option costs are equal. Then all variance (and adjustment) takes place with the weighted factors. An adjustment procedure appropriate to this situation is the following:

$$K' = K + \lambda \alpha (x_c - x_m) \tag{3-2}$$

where $\alpha = 1 - \dfrac{|(C_c - C_p)|}{C_c + C_p}$

C_c is the cost of the chosen alternative and the remaining variables are defined as in equation 2-7.

In this expression, α takes the range of $0 \leq \alpha \leq 1$ and is inversely proportional to the difference in costs between the chosen (C_c) and predicted (C_p) options. Adjustments are then largest when the cost difference is small.

The cost-benefit formulation differs from the additive MAU form in the combination rule of the factors and in the adjustment procedure. The two formulations are compared in the experimental study (Section 4) to see if the potential performance advantages of the cost-benefit form outweighs the additional complexity and training time of the purely additive model.

3.2 Continued Sampling of Information

Up to this point, the analysis of the information seeking task in advanced aircraft operations has dealt exclusively with single-sample situations--tasks were the possible information options are scanned, a single option or set of options selected and observed, and an action taken. The more realistic but also much more complex case is that of sequentially sampling different sources until some confidence level is achieved prior to action execution. This is termed continued sampling of information.

Continued sampling occurs frequently in the cockpit. The pilot receives a radio communication regarding possible threats. The radar is set to wide envelope scanning. Detection of a threat then leads to use of narrow envelope radar or infrared signature analysis until the threat identity is established with sufficient confidence to take action.

The above scenario fits nicely into the modeling paradigm of optional stopping. Optional stopping occurs when the decision maker must choose between accepting a currently available action or continuing to sample further information to achieve greater certainty. A wealth of experimental information has been accumulated in this context. In medical diagnosis, for example, Pitz (1968) found that the cost of each diagnostic test is compared with the expected gain which it provides. Descriptively, it is found that people purchase information until posterior odds in favor of the most likely hypothesis reach some critical value. The critical value decreases and the sample size increases. Levine and Samet (1973) found that subjects purchase more information prior to a decision where the information was (a) higher reliability, (b) higher update frequency, and (c) increased degree of conflict. Also Snapper and Peterson (1971) found that the degree of diagnosticity also influenced information purchasing, along with cost and prior probability.

Unfortunately, the optional stopping behavior has been successfully modeled only in the two hypothesis case (Edwards, 1965; Slovic, Fishburn and Lichtenstein, 1977). The advanced aircraft situation and indeed even the current task simulation exhibits a large number of distinct hypotheses. Each combination of threat type and location represents a distinct state.

The problem can be seen in Figure 3-1, a modification of the decision tree of Figure 2-3. Each possible information sampling can be

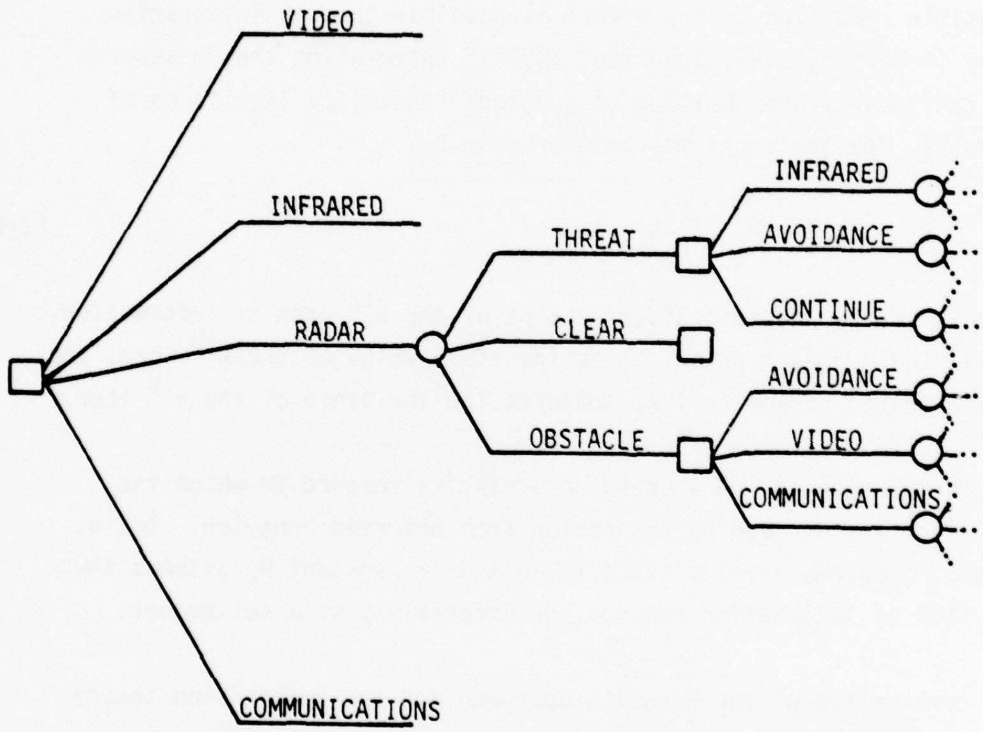


FIGURE 3-1.
CONTINUED SAMPLING DECISION TREE

represented as an action with definable consequences (costs, delays, etc.). Subsequent information samplings and actions along this branch are contingent on the information received. In order for the tree to be useful, all of the possible sequences of messages, actions, and events must be definable.

A possible reduction of the effort is possible through integration theory (Anderson, 1965; Shanteau, 1970). Integration theory asserts that the step-by-step buildup of judgment (estimated likelihood of avoidance, for instance) may be expressed by:

$$R_k = R_{k-1} + W_k \left(S_k - R_{k-1}\right) \qquad (2\text{-}3)$$

Where R_k is the judgment after receipt of the k^{th} item of information, R_{k-1} is the judgment prior, S_k is the scale value of the k^{th} item, and W_k is a change parameter that measures the influence of the k^{th} item.

This formulation can be a useful descriptive measure in which the parameters are derived by regression from observed behavior. Again, however, problems develop since the use of a constant W_i assumes that each item of information reduces the uncertainty by a set amount.

Some combination of the Bayesian approach and the integration theory method appears useful. The possible information acquisition choices may be categorized into three classes, according to the form of model:

(1) Bayesian - Only a few distinctly different messages are possible, precise estimation of probabilities is necessary, and the prior and conditional probabilities are available with some accuracy.

(2) Integration Theory - A given information source provides a wide variety of messages but the message influence is constant in terms of diagnosticity.

(3) Unmodeled - The information choice is too poorly defined to allow either of the above forms. In this case, an overall judgment of the value of the information may be assigned.

The above forms may be used at different parts of the decision tree faced by the operator. In all of the above cases, a posterior estimate of the state is necessary from the previous information sampling. This posterior estimate may come from an updata calculation such as from equation 3-3 or from a subjective estimate or threshold response.

3.3 Process Model of Information Seeking

The information seeking and decision making models described up to this point have dealt primarily with the processes of evaluation and selection of an information source. Implicit in this analysis are considerations of the characteristics of the information sources, the means of transmision, the type of display presentation and formatting, and the subsequent action decisions. In order to represent (and optimize) relations between each of these stages, a complete process model is needed.

A generalized organization of the process model in block form is shown in Figure 3-2. Inputs from each of the information sources (radar, fault detection, etc.) are processed in preparation for display. The processing results in determination of attribute levels for each input, and

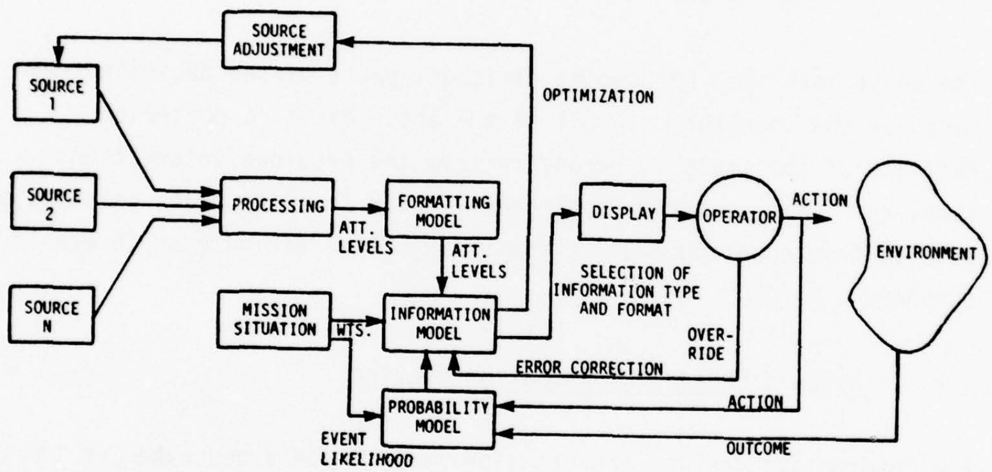


FIGURE 3-2.
PROCESS MODEL OF INFORMATION FLOW

these attribute levels are routed to the formatting program. The formatting program determines the impact of candidate display formats on a subset of the information attributes--delay, effort, and discrimination, for example. The full set of attributes for each option and format is then transferred to the information value model for evaluation and selection. The model determines the most effective type of information and formatting in the situation at hand, and manages the display accordingly.

The portions of the information system described up to this point have been operating in a deterministic input-output mode. The remaining portions of the flow chart show the adaptive elements of the program. The first feedback loop is found between the operator and the information value model. After observing the selected information, the operator may use it, dispense with it, or request other information. If the operator overrides the information choice, this is an input to that program, resulting in the operation of the error correcting adjustment procedures described in Section 2-3 and 3-1. A probability adjustment feedback is seen between the environment and the probability model. The actions and subsequent outcomes are fed into the probability model and probability estimates are built up by observation and adjustment. For each mission situation, variations in decision strategy and event likelihoods are input from a mission situation data base. The final form of feedback is the adjustment of the information sources using the information value model. An optimization program based on gradient search can determine the sensor characteristics--radar scan volume, power, direction, etc. needed to maximize the processed information attributes.

Implementation of the above system requires an elaborate model specifying the influences of source type, processing characteristics, format specification, and situation demands on the information contribution. The process may be viewed as a series of transitions between each of the

elements in the information cycle. The information begins the cycle with a set of characteristics, which are degraded or enhanced with each element. For example, radar may pick up a set of threats. Processing may identify the threat types and determine their course. Formatting the information graphically may reduce the location accuracy, add to the noise present, and result in a display time delay. The mission situation, finally, will specify the importance of rapid offensive action or avoidance.

Each of the transitions described above may be represented using matrix methods. For example, the influence of display format on information attributes may be described using a matrix of the type of Figure 3-3. The information attributes correspond to the impact of the information on the given dimension of value. The elements of the matrix reflect the strength of communication of each dimension or attribute by the given display format. For example, an alphanumeric display may preserve the precision level of a pitch or roll reading, but may result in cognitive loading and delay. A symbolic representation on the other hand, may degrade the precision level but tends to be rapidly assimilated. In sum, the matrix techniques provide a means of expressing the influence of each type of processing on the information characterisitcs.

A linking together of matrices to represent much of the information management process is shown in Figure 3-4. Tracing the path between processes, it can be seen that the first matrix relates information sources to attributes. Essentially, the sources are decomposed into costs, delays, and other consequences independent of the display format. This is equivalent to the mapping between mission situation and decision attributes discussed in Section 2.3.5. The matrix elements are determined by subjective estimation or by observation and adjustment. The second matrix, relating information attributes to display format, shows how the attributes are affected by the display format. The final matrix is

ATTRIBUTES	DISPLAY FORMAT				
	ALARM	ALPHANUMERIC	TEXT	SYMBOLIC	PICTORIAL
TIME DELAY	.1	.3	—	—	—
COGNITIVE LOADING	.5	—	—	—	—
COURSE MANAGEMENT	—	—	—	—	—
RESOURCE MANAGEMENT	—	—	—	—	—
THREAT IDENTIFICATION	—	—	—	—	—
CHANNEL SECURITY	—	—	—	—	—

FIGURE 3-3.
INFORMATION TRANSFER MATRIX

	TIME DELAY	COGNITIVE LOADING	COURSE MANAGEMENT	RESOURCE MANAGEMENT	THREAT IDENTIFICATION	CHANNEL SECURITY
INFRARED	.8	.4	–	–	–	–
WIDE ENVELOPE RADAR	.5	–	–	–	–	–
NARROW ENVELOPE RADAR	–	–	–	–	–	–
NAVIGATION	–	–	–	–	–	–
PROPULSION/FUEL SYSTEM FAULT	–	–	–	–	–	–

	ALARM	ALPHANUMERIC	TEXT	SYMBOLIC	PICTORIAL
TIME DELAY	.1	.3	–	–	–
COGNITIVE LOADING	.5	–	–	–	–
COURSE MANAGEMENT	–	–	–	–	–
RESOURCE MANAGEMENT	–	–	–	–	–
THREAT IDENTIFICATION	–	–	–	–	–
CHANNEL SECURITY	–	–	–	–	–

	CRUISE/NAVIGATION	RECONNAISSANCE	TARGET MONITORING	TARGET INTERCEPT	DEFENSE
ALARM	–	–	–	–	–
ALPHANUMERIC	–	–	–	–	–
TEXT	–	–	–	–	–
SYMBOLIC	–	–	–	–	–
PICTORIAL	–	–	–	–	–

FIGURE 3-4.
LINKING OF INFORMATION TRANSFER MATRICES

the weighting of the attributes according to importance by mission situation. The adaptive or direct elicitation procedures described in Section 2.3 provide estimates of these elements. Should additional dimensions of transmission mode or decoding form be present, matrices may be defined for these also.

Once the individual matrices are defined and filled in, the best set of information management options may be selected through a multiplication of the matrices. The source, processing, and format with the greatest net contribution can then be identified. Conversely, the sources may be adjusted through a search procedure to maximize the aggregate contribution for each set of options. The matrix representation also allows for various forms of sensitivity analysis. Each aspect of source characteristic, processing mode, or display format may be varied to determine its impact.

3.4 Operator Loading

The task loading on the flight officer is expected to vary widely during a mission. The loading may be a result of decision complexity, the speed or frequency of decision-making, or the number of tasks (secondary task loading) demanded of the operator. The result of the excessive loading may be degraded decision making, "narrowing" to a subset of factors, inadequate response time, or the ignoring of certain processes. These suboptimal behaviors may be averted through use of several different forms of aiding:

(1) Reducing information throughput at heavily loaded times through use of a variable utility threshold.
(2) Changing the additive importance of time related factors (delay, speed, etc.) as the situation demands change.
(3) Providing greater amounts of unburdening through automation when the task complexity is excessive.

A necessary precursor to implementation of any of these forms of aiding is the development of a methodology for measurement of immediate workload. A useful concept for the assessment of workload has been proposed by Johns (1973). He divided the broad area of human operator load into three functionally related attributes:

(1) Input load - factor or events external to the operator.
(2) Operator effect - internal to the operator.
(3) Performance - data outputs generated by the operator which serve as inputs to system components.

Some measures of performance that fall into these categories are listed in Figure 3-5 (after Johannsen, 1976).

Measures of operator load are of great concern and traditionally regarded as operator workload. In time line analysis (e.g., Greening, 1978), the execution times of all subtask elements are assessed. It is assumed that available time margins or expected time stress correlate with level of effort expended by the operator.

In information processing studies, the operator's channel is regarded as an information processing element with a fixed, limited channel capacity. Three major approaches are considered:

(1) Secondary or loading task - to measure spare mental capacity.
(2) Control theoretic measure - time or frequency domain (amplitude or power spectrum density measures) of human controller models (Baron and Levison, 1975).
(3) Information Theory.

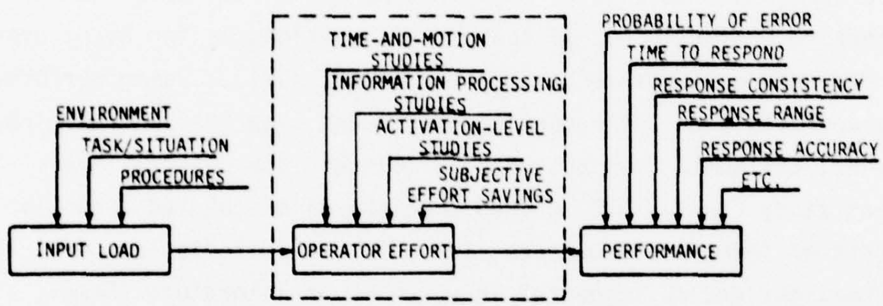


FIGURE 3-5.
ATTRIBUTES OF OPERATOR WORKLOAD

One major effort of man-machine system modeling is to provide an accurate model of human operator with predicted operator effort and performance as a function of the given task situation. A major limitation of this approach is due to the fact that human behavior is not context-free, i.e., it strongly reflects the task environment. If one looks at flight control systems that include control with respect to continuous events, then one can subsume most analytical models within the very specialized category of control theory.

There appears to be a level of load that maximizes human information processing performance. If the human's workload is too high, overload and degraded performance occurs (Van Gigch, 1971). Human performance also degrades when the human is underloaded (Van Cott and Warrick, 1972). However, the human does not usually maintain the optimal level. A recent study (Hart, 1979) showed that the pilots wanted excessive amounts of information onboard, including cockpit displays of traffic information; and as suggested in a review of literature (Samet, et al, 1976), the operator typically desires more information than can be meaningfully used.

With the use of model-based aiding of information selection, it is possible to adaptively adjust the pilot's information load. The computer can observe the operator's actions and, using a model of human behavior, decide on the appropriate level of human workload. The computer can then adapt the information presentation to the model.

From an information system point of view, a simplified model is to view the pilot's information and decision load as reduction of information content:

$$\Delta H_i = [\dot{H}_i(x) - \dot{H}_i(y)]\ \Delta t;\ i=1,..n$$

Where $H(x)$ and $H(y)$ are information content rates (in bits/sec) that the operator receives from, and provides to the system. Four variables that affect the information load are: (1) the information rate (speed stress), $H_i(x)$, (2) the information complexity, $H_i(x)-H_i(y)$, (3) the number of processes (subtasks), n and (4) the level of interaction among processes; for processes i and j, this can be represented by $Cov(H_i(y), H_j(x))$, $cov(H_j(y), H_i(x))$. These variables of input load could serve as good criterion for load adjustment provided that the input load and performance relationship for specific tasks are established.

An alternative in the experimental setting is to use a secondary task as a measure of pilot information load. Here the operator is considered as a single-channel information processing system. This single channel concept can be shown to be realistic when applied to the operator's ability to deal with information which requires attention. The use of a secondary task of a non-information nature seeks to provide an indicator of how much additional work the operator can undertake. Alternatively, the secondary task can induce changes in the level of processing performance which are indicative of the operator's information load.

The secondary task technique is a sensitive indicant of primary task demand when perceptual motor activity makes up the demand (Rolfe, 1973). However, lack of validation with secondary task results has limited this approach to essentially one of a laboratory tool. The technique has shortcomings regarding interference with performance by the secondary task, and with producing confounding factors of arousal and fatigue as well as influencing task factors such as information load, information speed, rate of responding, stimulus compatibility, and memory load (Brown, 1963).

A simple approach is that of time line analysis. The input demand represented by number of messages (Chu and Rouse, 1979) or by total MAU values in the message set (Samet, 1978) show the robustness of these measures in both flight management and political military scenarios. Again, problems develop as the supervisory control situation deals primarily with top level, discrete events, rather than molecular items. Queueing models are better suited to this domain.

Queueing models have the ability to do a good job of predicting the average fraction of time the pilot is busy, (Server occupancy measure), given a good description of event arrival times, task completion times, and the priority of tasks. Queueing models also enable the model prediction of (momentary) peak load as a function of input demands. In the most complicated situations, queueing theory only provides bounds for predicted performance measures.

It was proposed in Chu and Rouse (1979) that the operator load be regulated through a set of thresholds on input demand; when demand exceeded the upper threshold, the upcoming task was routed to automated function, while, when demand fell below the lower threshold, the upcoming task was routed to the operator. A look-up table or a fast model had to be maintained to relate the operator effort and performance to the input demand (see Figure 3-6).

Several experimental studies (Chu and Rouse, 1979) demonstrate that the queueing model is capable of representing the multi-task decision making situation, and accurate at predicting such system performance measures as delay time and server occupancy. The simple measure of server occupancy was found to correlate highly with the subjective effort rating in a combined monitoring and control multi-task situation. An adaptive threshold policy for routing input demand, which employed a fast-time model based on

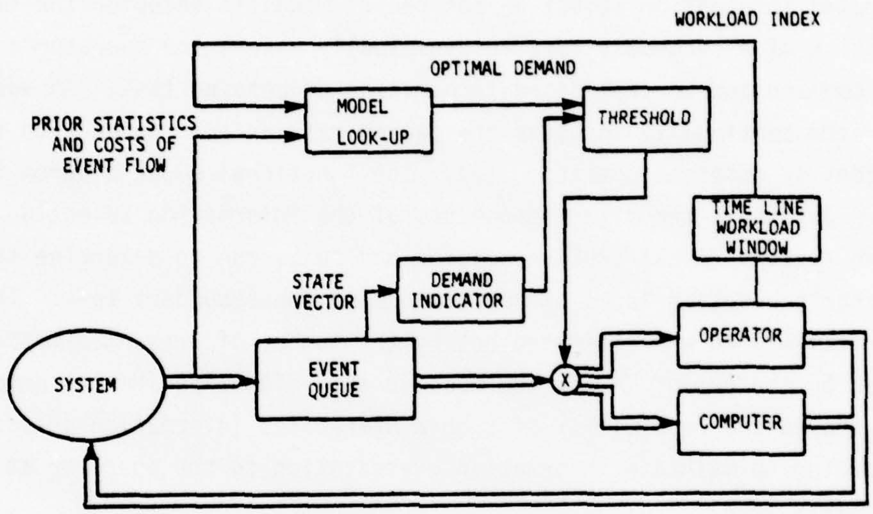


FIGURE 3-6.
ALLOCATION OF DECISION MAKING RESPONSIBILITY BETWEEN
OPERATOR AND COMPUTER IN MULTI-TASK SITUATION

a queueing simulation, were shown to significantly improve performance time and were better accepted by the participating subjects compared with a fixed threshold policy.

Experimental studies of the MAU approach to modeling and dynamically controlling information flows have also shown promise. Samet's (1978) automated information selection and pacing model is based on the implementation of a secondary task to dynamically assess the operator's load in a command and control based information processing task. An adaptive algorithm continually adjusted the pacing rate in accordance with fluctuations in assessed operator load. The functional block diagram in Figure 3-7 shows the major components of the information selection and pacing system. A calibration session had to be run to determine the operator's baseline level of performance on the secondary task. The information load was estimated not by the number of presented messages but rather by the sum of MAU in the message set. The experimental demonstration showed the feasibility of such a user-based information selection and pacing to maintain information presentation to the operator at an acceptable level.

A combination of the MAU and Queueing model formulations appears to have the most promise in the advanced aircraft situation. The hybrid approach would compensate for operator loading through the following three modes:

(1) Adjusting a threshold of information presentation.
(2) Adjusting additive factors for evaluating the information.
(3) Adjusting the allocation of responsibility between pilot and computer.

The criteria for adjustment would take the form of:

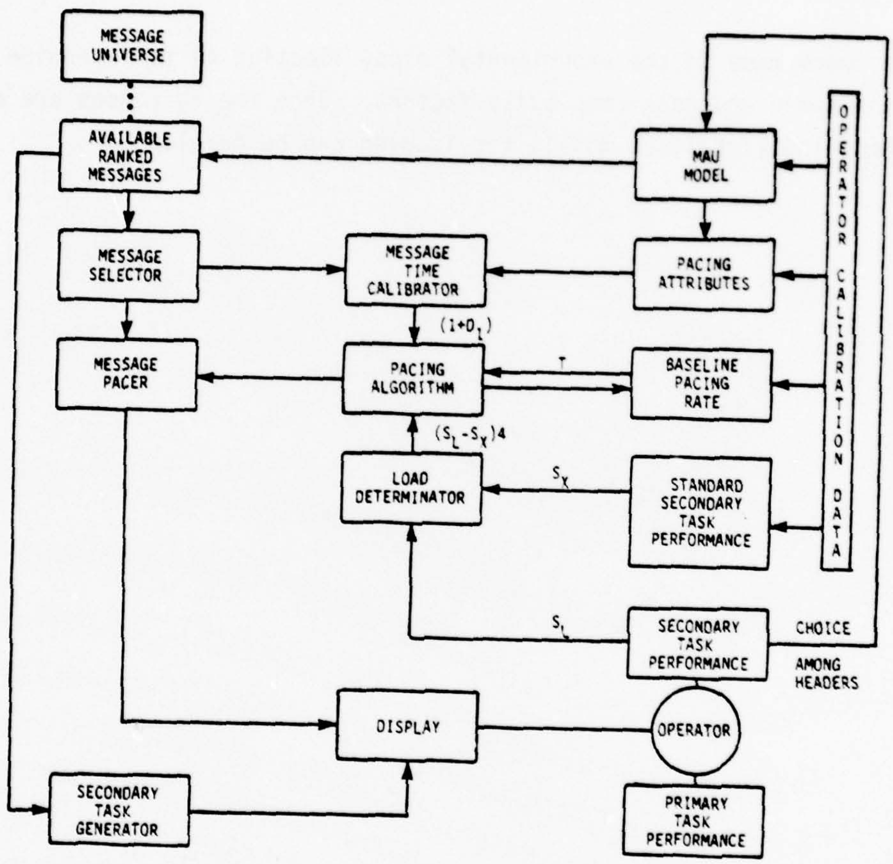


FIGURE 3-7.
INFORMATION SELECTION AND PACING
SYSTEM (SAMET, 1978)

(1) The measured task performance.

(2) The predicted task load, from indicators of complexity, speed, and task interference.

(3) The subjective operator input.

Tests were made in the experimental study (Section 4) to determine responses to the speed and task complexity factors. Once the responses are ascertained, individualized models for loading can be developed.

4. EXPERIMENTAL STUDY

4.1 Overview

A set of experimental studies were performed to determine the efficacy of alternative configurations of the adaptive decision model under different situational conditions. An advanced aircraft simulation was employed, modified slightly from that used in the previous year's studies (Steeb, Davis, Alperovitch and Freedy, 1978). Individual subjects were required to pilot a simulated aircraft in a changing, hazardous environment. In doing so, the operators were able to select from a variety of forms of information concerning the multiple threats encountered, and take either evasive or aggressive actions. Performance comparisons were made in the study between cost benefit and multi-attribute utility-based models. Also, the effects of speed stress and decision complexity loading on model performance were determined.

4.2 Hypotheses

The following experimental hypotheses were tested:

(1) In the limited resource situation, the cost-benefit model will result in greater overall score, less cost expenditures per cycle, and greater operator acceptance than the additive MAU model.

(2) The cost-benefit model will achieve a greater decision prediction rate than the additive MAU model in the limited resource task.

(3) The decision models will exhibit increased variability of weights and decreased prediction rates as the decision complexity changes phase by phase and as the speed increases.

4.3 Task Simulation

The task simulation is patterned after an important and representative information acquisition task--multiple threat intercept operations in advanced aircraft. The simulation is an adaptation of the remotely piloted vehicle supervision task employed in the previous study (Steeb, Davis, Alperovitch and Freedy, 1978). Briefly, the simulation requires the operator to control an advanced aircraft in a hazardous mission. Threats of uncertain capability and location are encountered repeatedly. The operator has the option of accessing several forms of information about the threats. The forms of information differ in threat discrimination capabilities, transmission costs, processing delays, and potential of detection.

4.3.1 Displays and Controls. The simulation uses a computer-generated CRT display, illustrated in Figure 4-1. The environment and aircraft are shown as they would be in a moving-map display. Sets of threats appear at random positions at the upper edge of the display and move downward at a constant velocity. The operator can move the vehicle symbol horizontally to one of eleven different pathways to avoid the threats, or he can remain on course and take an aggressive action against one of the threats. The actions open to the operator are primarily decision making in nature. Dynamics of control are minimized since the threat and vehicle velocities are held constant.

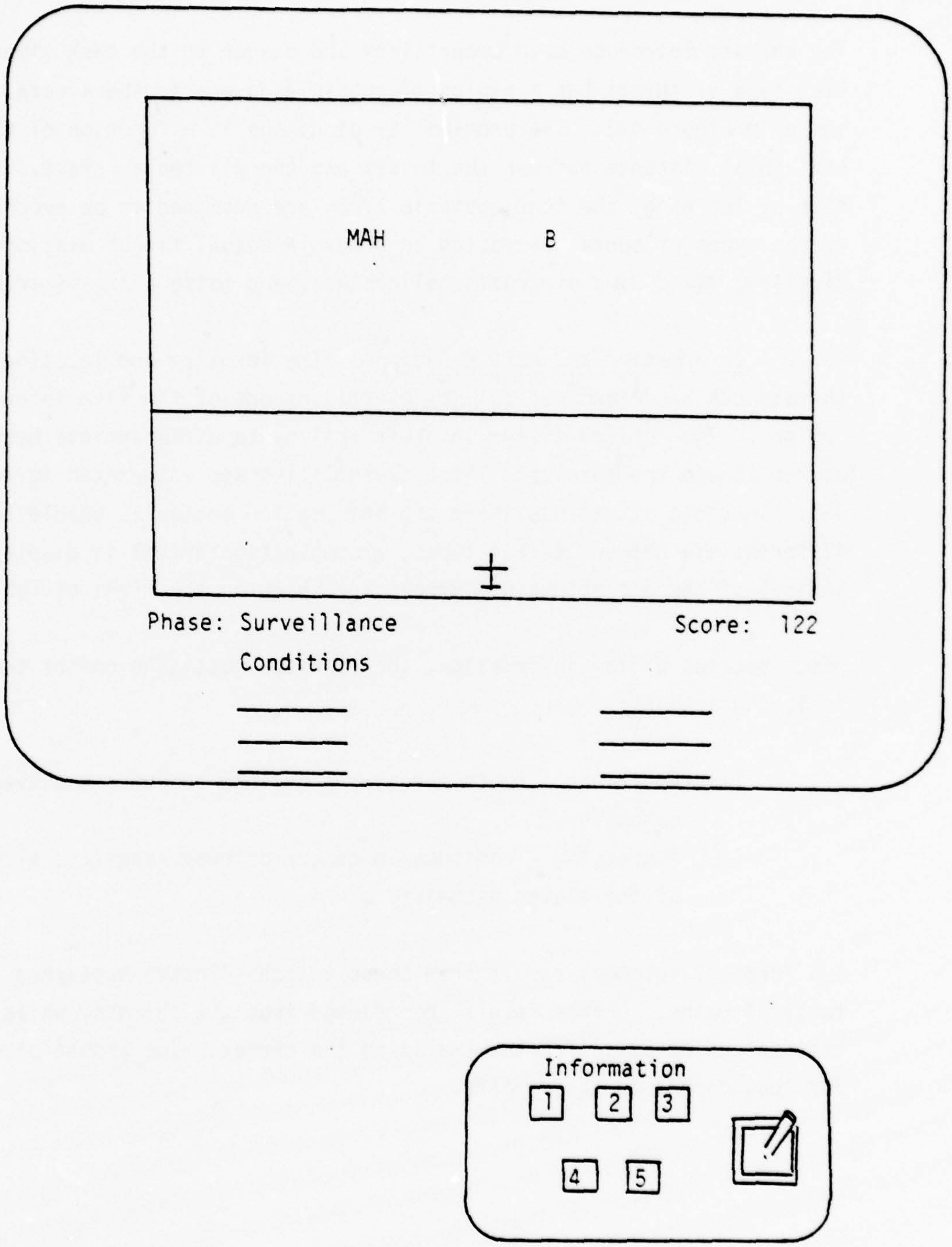


FIGURE 4-1.
SIMULATED DISPLAY AND COMMUNICATIONS PANEL

The threats introduce both uncertainty and danger to the task simulation. Each type of threat has a region of possible damage to the aircraft as shown in Figure 4-2. The probability of damage is a function of the horizontal distance between the threat and the piloted aircraft. For ease of learning, the four obstacle types are designed to be evocative of the types of contact expected to occur in actual flight missions--missiles, fixed-wing aircraft, helicopters, and false alarms (birds).

4.3.2 <u>Information and Action Options</u>. The identity and location of the threats can be determined only by exercising one of the five information options. The options differ in their ability to differentiate between and to locate the threats. These capabilities are enumerated in Table 4-1. In those situations where the information option is unable to differentiate between threat types, a combination symbol is displayed. Several of these combination symbols are shown on the right of Table 4-1.

After receipt of the information, the operator must take one of the following actions:

(1) Avoidance - route the aircraft alone one of the eleven pathways.
(2) Aggression - continue in center pathway, and fire along one of the eleven pathways.

Two forms of outcomes result from these actions--losses sustained and tactical gains. Losses result from damage from the threats, while tactical gains arise from neutralizing the threat. The amount of gain and loss depend on the payoffs.

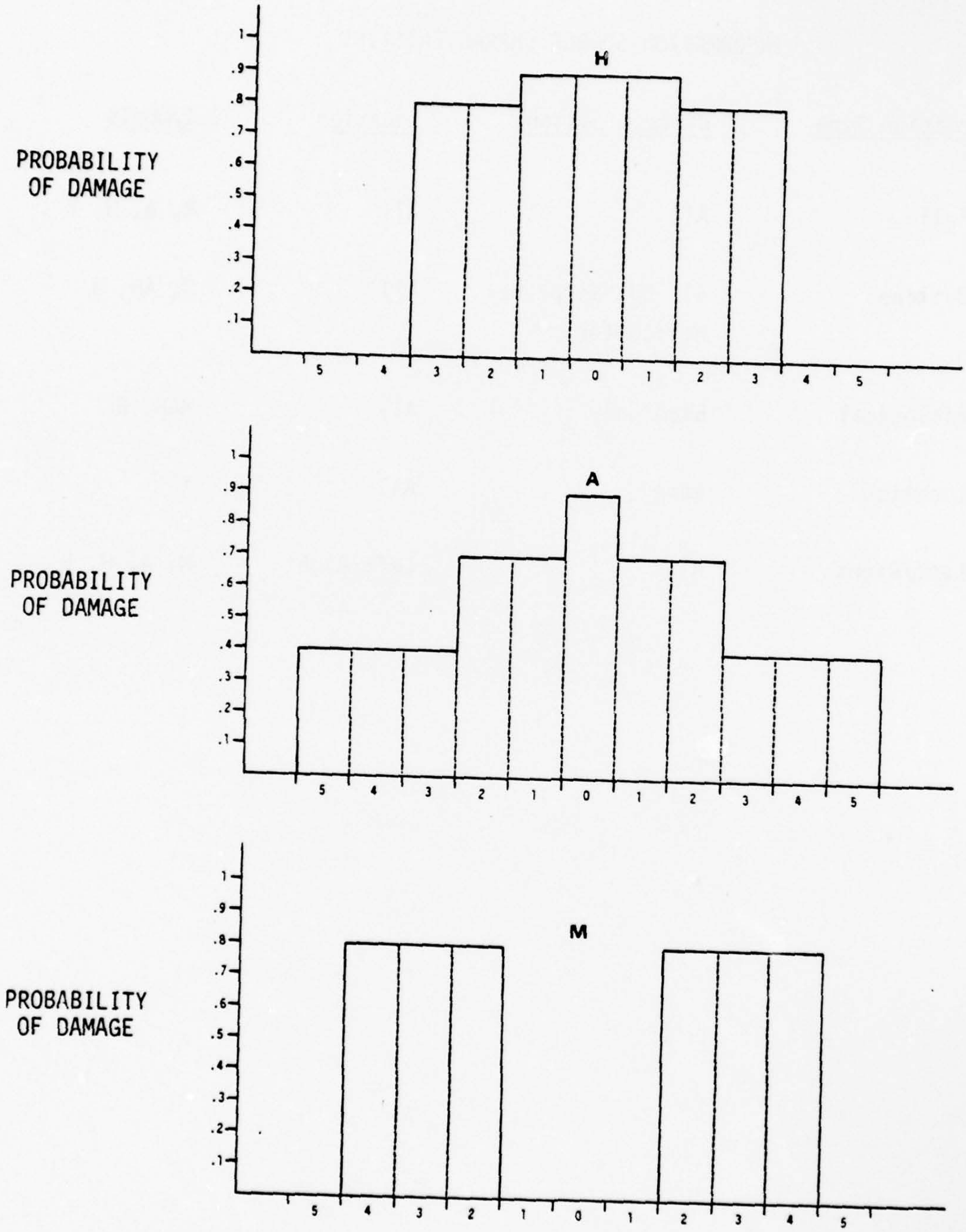


FIGURE 4-2.
THREAT CHARACTERISTICS: HELICOPTER (H), AIRCRAFT (A), MISSILE (M)

TABLE 4-1

INFORMATION SOURCE CHARACTERISTICS

Information Type	Discrimination	Location	Symbols
1. Full	All	All	M, A, H, B
2. Outline	All but airplane/ helicopter	All	M, AH, B
3. Biological	Bird only	All	MAH, B
4. Location	None	All	X
5. Left/Right	All	Left/Right	M, A, H, B

Sequence. The task consists of a series of similar, connected decisions. Prior to the appearance of any threats, the operator is appraised of the circumstances surrounding the upcoming decision. He must then make an information selection by pressing one of the buttons shown in Figure 4-1. A set of two threats is presented at the top of the screen and moves downward. If "full" information is selected, the differentiated symbols in their proper location move down the screen. If "outline" information is selected, the missile and bird symbols are differentiated, but helicopters and airplances are represented by a single, non-differentiating symbol (AH). Similarly, "biological" information will use a single, non-differentiated symbol to represent either missile, airplane, or helicopter. "Location" information provides no discrimination. A symbol denotes the location but not the identify of threats. "Left/Right" information finally, discriminates the obstacles using the standard symbols, but locates them only as lying in the left or right half of the screen.

The task moves on continuously, just as an airborne mission does. If the operator does not select an information choice in the time allocated (about 5 seconds), location information is provided by default. Following information receipt, the operator must make an action selection before the threats reach the decision limit (a line approximately 2/3 of the distance down the screen).

4.3.3 Situational Conditions. The stages of an aircraft mission can be characterized by such factors as danger, difficulty, system reliability, and communications security. Accordingly, the task simulation was designed to include many of the same factors. The situational conditions are not considered to be experimental variables, but are factors contributing to task complexity. The conditions are:

(1) Degree of danger - This is the distribution of possible threats in a given phase. A vector of prior probabilities of occurrence of the four threat types is assigned to each phase.

(2) Costs - a different cost is assigned to each information choice. This is the number of points expended for use of the information.

(3) Detection - The increased danger on the succeeding decision due to use of a given information source. An additional probability of loss is associated with each of the threats.

(4) Delay - The delay in seconds before actual display of the information. This may also be quantified as the percent of the distance to the action limit before the information is displayed.

(5) Payoffs - Different payoffs in points are made for avoidance of or damage sustained from the threats, and for successful or unsuccessful aggressive actions toward the threats. Each of the payoffs vary phase-by-phase.

The presentation of conditions is organized into three distinct mission phases--cruise, surveillance, and aggression. Each phase has set levels of danger, detection, and payoffs. For variability, the costs and delays are varied smoothly and periodically within each phase. All conditions are displayed to the subjects.

The phases differ in decision complexity. One phase, aggression, has only three non-dominated information selection alternatives (full, outline, and biological information) and four decision attributes (cost, time delay, avoidance gain, and aggressive gain). The cruise phase is intermediate in complexity, with four choices and four attributes, and the surveillance phase has maximum complexity, with five choices and five attributes. The phases and their associated conditions are:

(1) Cruise - medium payoffs for both avoidance and aggressive actions; variable costs and delays; no possibility of detection.

(2) Surveillance - high payoffs for avoidance, minimal for aggressive actions; variable costs and delays; high probabilities of detection with certain information sources.

(3) Aggression - high payoffs for aggressive actions and delays, minimal for avoidance; variable costs and delays, and no possibility of detection.

Each phase consists of ten decisions in sequence. A session consists of two to three complete sets of the three phases. The actual number of decisions made in a session depends on the cost expenditures, since the task terminates when the cost limit is reached.

4.4 Decision Model

4.4.1 General. The decision faced by the operator is a two-stage information/action sequence, as shown in Figure 4-3. The decision space is fairly large, resulting from the five possible information choices,

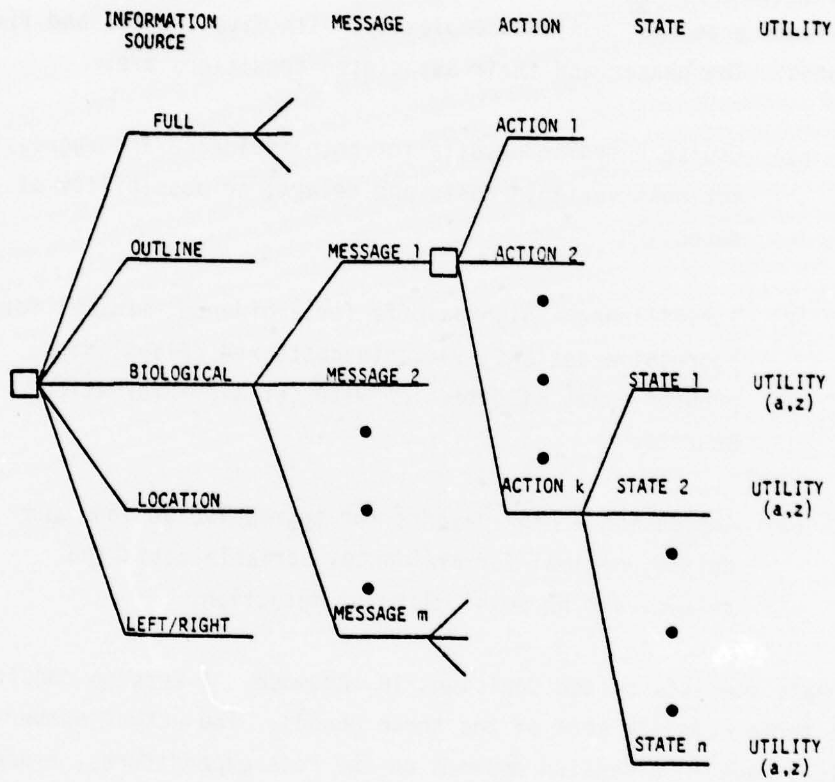


FIGURE 4-3.
COMPLETE DECISION TREE

22 subsequent action choices (avoid or attack along each of the 11 pathways), and 330 possible states (combination or threats). A variety of multidimensional consequences result from the resulting space, stemming from the various combinations of outcomes, costs, payoffs, delays, and future impacts.

A purely analytical formulation of this is intractable, just as it is for most operational information seeking decisions. Categorization is an obvious means of reducing the complexity of the decision. Here those elements in the decision similar in consequence can be classfied together. For example, the number of states can be reduced from 330 categories to 6 categories by classifying according to threat combination (ignoring specific location). The probability of each message and state then can be calculated from the prior probabilities of each of the threats and the information source characteristics. The actions can be similarly categorized as avoid or attack without regard to location. Probabilities of each outcome type--avoidance, damage, missed attack, and hit--can be established by observed frequency. To do so, a probability estimate must be associated with each combination off information, message, action, and state. After categorization, 90 such combinations are present. These probabilities were determined from a series of pilot system tests, and were intended to be representative of the performance of the typical subject. Estimates specific to each subject were not made. The consequence levels (the attribute level vector) associated with a given information choice in a given situation are calculated by folding back the decision tree. The favored action choice after receipt of a given message is determined in the same fashion.

4.4.2 Decision Attributes. Five consequence-related attributes are employed in the decision model. The attributes are the following:

(X_1) Cost - The cost of the communication in points (costs range from 0 to 13 points).

(X_2) Delay - The time in seconds before display of the information (delays ranged from 0 to 5 points).

(X_3) Detection - Increase in the probability of damage on the subsequent decision (the probability increase ranged from 0 to 20 percent).

(X_4) Vehicle loss - Expected (probability weighted) level of damage to own vehicle (range: 2 to 14 points).

(X_5) Offensive gain - Expected level of damage inflicted on adversary (range: 2 to 14 points).

X_4, the vehicle loss attribute is computed according to the following expression:

$$X_4 = \sum_{\substack{\text{message}\\ y}} \sum_{\substack{\text{action}\\ a}} \sum_{\substack{\text{state}\\ z}} \{P(\text{avoid} \mid y,a,z) \cdot \text{Payoff (avoid)} - P(\text{damage}) \mid y,a,z) \cdot \text{Payoff (damage)}\}$$

X_5, the offensive gain attribute is calculated in an identical manner using the probabilities and payoffs for hit and miss.

4.4.3 Model Form. The five attributes may be combined into an evaluation function using either of the two forms described in Section 3.1: the linear additive MAU function or the cost-benefit function. The MAU function is simply the linear weighted combination of the five factors:

$$MAU[I_s] = \sum_{i=1}^{5} K_i \cdot X_{is} \tag{4-1}$$

Where MAU $[I_s]$ is the aggregate (multi-attribute) utility of information choice I_s, X_{is} is the level of attribute i associated with information choice I_s, (calculated using Equation 2-6) and K_i is the importance weight of attribute i. It should be noted that the program does not have access to the true state of the environment. All values are calculated according to a priori probability distribution.

The cost-benefit formulation is a modification of Equation 4-1:

$$\text{Cost-benefit ratio } [I_s] = \frac{1}{C_s} \sum_{i=1}^{4} K_i \cdot X_{is} \qquad (4\text{-}2)$$

Where C_s is the cost of information choice I_s and the other variables are defined as above.

Weight Estimation. Similar forms of adaptive weight estimation were utilized for the MAU and cost-benefit models. Adaptive estimation for the the MAU models was performed using the pattern recognition approach described in Section 2-3. Prior to the automated sessions, each subject experienced manual selection sessions of two to three sequences of the three phases (cruise, surveillance, and aggression). The length of the session was governed by the information usage. The session terminated when the cost limit was reached. A separate 5-element weight vector was maintained for each of the three phases. These three vectors were then "frozen" for use in the automated information management sessions experienced later.

The estimation process for the cost-benefit model was slightly more involved. When a discrepancy between predicted and actually chosen information sources was present, the four attribute weights (see Equation 4-2) were adapted just as the five attributes of the MAU model. The

degree of adaptation depended on the cost difference between the predicted and chosen sources. If the choices were close in cost, the same amount of movement of the weights was prescribed as in the MAU formulation. If a large difference in cost was present between the chosen and predicted options, no adjustment was made, since the choice may have simply been due to the cost difference. An intermediate extent of adjustment was provided with moderate differences in cost. The variable adjustment rule was implemented in the simulation through the definition of cost difference thresholds.

4.4.4 Performance Measures. The close coupling of operator and aiding system requires evaluations of (1) the overall system performance and (2) the performance of the decision model.

System Performance. The overall system performance is described using a single index, the score. The score is derived from the number and the cost of errors committed and the communications costs expended:

SCORE = (PAYOFFS) - (PENALTIES + COMMUNICATION COSTS)

The score is presented to the subject as a single index of performance, and his compensation depends to a large extent on the measure. The complexities of having speed as a second, independent measure are avoided by presenting the task at a set pace.

Decision Model Performance. The effectiveness of the decision model was evaluated in terms of behavioral prediction, operator acceptance, and information management performance. Prediction refers to the ability of the model to predict operator behavior in both the information and actual decisions. Outputs of the adaptive models were compared to actual operator choices during the unaided sessions.

4-1

Multivariate analysis of variance was used to analyze the distribution of information choices and the vectors of importance weights K_i. The dependent variables in these cases are (1) the frequency with which each information type is chosen, and (2) the vectors of K_i by subject and phase.

4.4.5 Subjects and Procedure. The eight subjects participating in the study were recruited from nearby universities and military reserve units. They represented the type of personnel who might interface with computer-aided information systems. The subjects ages ranged from 21 to 34, and they had completed between two and eight years of college. Four were male and four female. Five of the eight had experience working with computers.

Each subject underwent one hour of orientation and practice prior to the experimental sessions. The experimental sessions consisted of four manual information selection sessions followed by four automated information selection sessions. The order of the sessions is shown in the repeated measures experimental design of Figure 4-4. Each experimental session consisted of two to three complete sequences of cruise, surveillance and aggression, the actual number depending on the point of resource depletion. A session lasted approximately 30 minutes and consisted of 60-80 decision cycles. The subjects were paid \$4.00 per hour and given a bonus to up to \$4.00 per hour contingent on performance.

GROUP	SUBJECT	LOW SPEED STRESS		HIGH SPEED STRESS	
		MAU MODEL	COST-BENEFIT MODEL	MAU MODEL	COST-BENEFIT MODEL
1	1, 2	A	C	B	D
	3, 4	B	D	C	A
	5, 6	C	A	D	B
	7, 8	D	B	A	C

NOTE: LETTERS DENOTE ORDER OF CONDITIONS

FIGURE 4-4.
EXPERIMENTAL DESIGN

SIMULATED DISPLAY AND COMMUNICATIONS PANEL

5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 General Observations

The choices of information acquisition and action selection in the simulation were found to be sufficiently varied and difficult to provide a good test of model-based information management. A wide variety of behaviors were observed and modeled. The task simulation was also sufficiently demanding to maintain a high level of subject interest. The subjects learned the task procedures readily and by the end of the training session, could effectively handle the task requirements in both slow and high-speed conditions and in manual and automatic modes.

5.2 System Performance

Performance under the three forms of information selection--manual, MAU-based automatic, and cost-benefit automatic--were found to be essentially equivalent. Significant differences in behavior were found between the three modes, but no significant advantages in overall score, perceived task difficulty, or perceived information selection effectiveness were noted.

A surprising finding was the significantly greater cost efficiency deriving from use of the MAU model compared to that found with the cost-benefit model. It was anticipated that in the resource-limited task simulation, the cost-benefit model would place a greater emphasis on conserving costs than would the MAU model. In fact, as shown in Figure 5-1, the MAU model resulted in 13% more decision cycles than the cost benefit model ($F = 9.91$, $df = 1, 4$, $P < .05$). With either model, aided performance correlated strongly with the previous manual performance. The cost-benefit model exhibited a correlation of .70 ($P < .05$) between the manual and

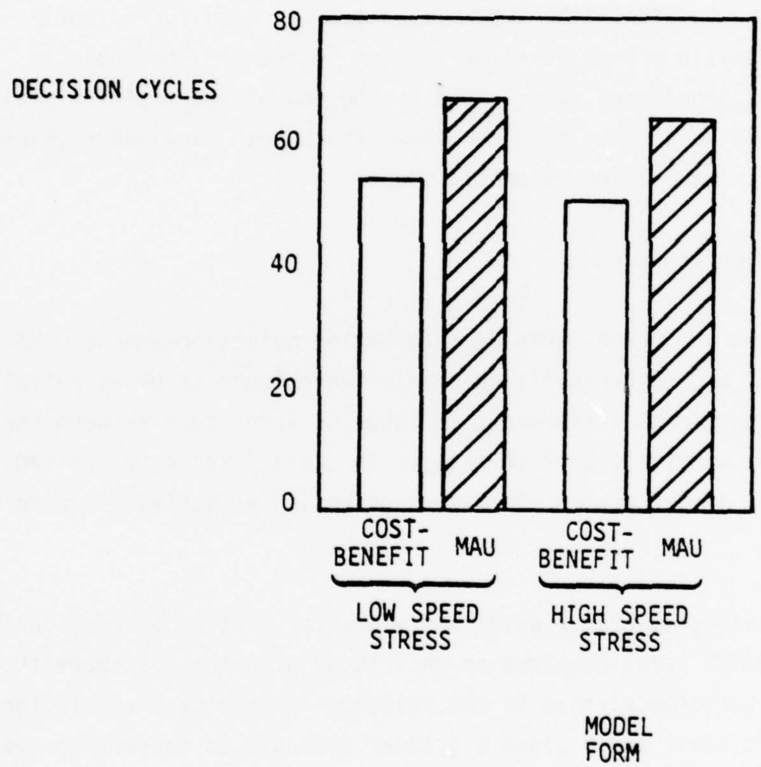


FIGURE 5-1.
NUMBER OF DECISION CYCLES COMPLETED AS A FUNCTION OF MODEL TYPE AND SPEED STRESS

THREAT CHARACTERISTICS: HELICOPTER (H), AIRCRAFT (A), MISSILE (M)

4-5

automatic scores, while the MAU model resulted in a .61 correlation ($P < .05$). In effect, good manual performance was necessary for good aided performance. The models did provide a certain amount of leveling, however. The variance of aided scores was significantly lower than the variance of the manual scores ($\chi^2 = 7.73$, df = 3, $P < .05$). The automation seemed to provide a smoothing of the more erratic manual performance.

5.3 Performance Components

Score performance under the manual conditions was found to be a function of several factors. Significant correlations were found between the score achieved and (1) the number of decision cycles ($r = .54$, df = 14, $P < .05$), and (2) the deviation from expected utility (DEU) with the MAU model ($r = .54$, df = 14, $P < .05$). Essentially, those subjects who placed the greatest priority on cost conservation and who acted most consistently in their decision policies achieved the highest scores.

Consistency with respect to the cost-benefit model did not appear to be as important to performance. Correlation of the DEU and the score did not reach significance with this model.

5.4 Aiding and Task Loading

The task simulation was designed to incorporate two different forms of task loading--speed stress and choice complexity. Speed stress was controlled by varying the time allowed for the information and action choices. Choice complexity was varied within each experimental session by definition of the three phases, each having different numbers of attributes and information choices.

Speed stress did not produce the expected significant differences in choice consistency and performance score. Apparently the two levels of speed stress were not sufficiently different to evoke major differences in behavior. Comparisons of the task difficulty estimates and the information effectiveness estimates did show a significant difference in perception of the difficulty and choice effectiveness between the low and high speed conditions (Wilcoxin matched-pairs signed-ranks test, df = 14, $P < .05$). The high-speed stress conditions were viewed as more difficult and the information obtained was seen as less effective than in the low-speed stress conditions. As might be expected, these differences were more pronounced in the difficult surveillance phase compared to the less complex cruise and aggression phases.

Task complexity, as represented by the variation in difficulty between the three phases, resulted in significant differences in behavior. Figures 5-2 and 5-3 show the policy weights and the distributions of information choices for each of the three phases: cruise at the top, surveillance in the middle, and aggression at the bottom. Each figure has four curves, resulting from the division of the MAU and cost-benefit sessions into high and low-scoring groups. Thus for each figure, the four curves are MAU-high performance, MAU-low performance, cost-high performance and cost-low performance. It should be noted in Figure 5-2 that there is no cost weight in the cost-benefit groups, as cost acts as a non-weighted dividing factor in the model.

The first phase, cruise, is of relatively low complexity. No detection was possible and the aggression option was chosen over the avoidance option in most instances. The straightforwardness of the decisions is reflected in both the policy and information choice distribution curves. In both figures, the four curves lie closely together, indicating that similar behavior is followed regardless of the performance attained or the model used.

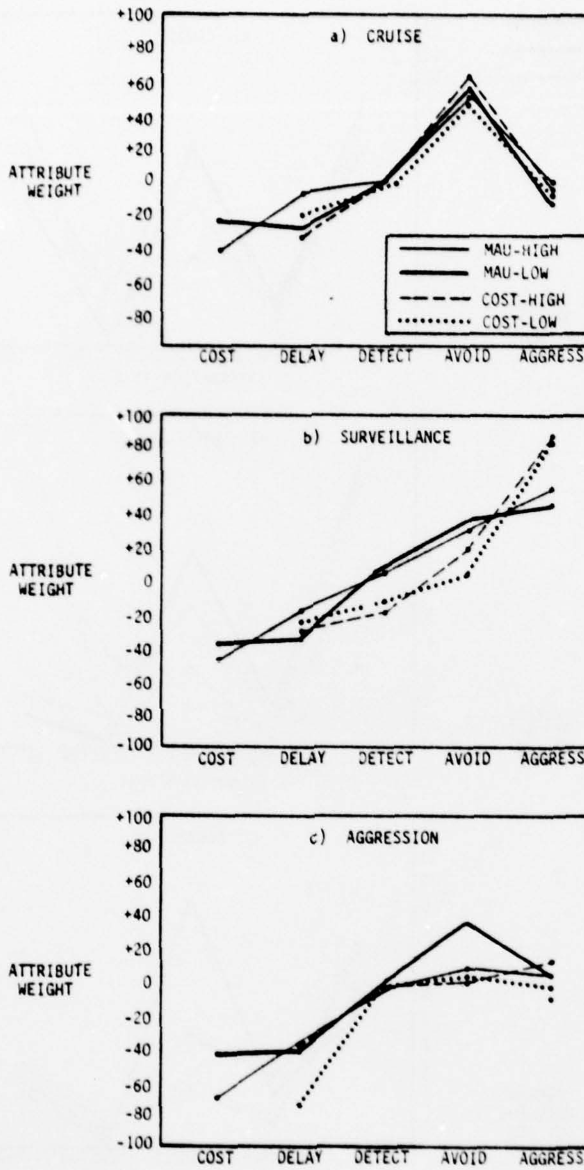


FIGURE 5-2.
ATTRIBUTE WEIGHTS AS A FUNCTION OF MODEL TYPE AND PERFORMANCE FOR a) CRUISE, b) SURVEILLANCE, AND c) AGGRESSION

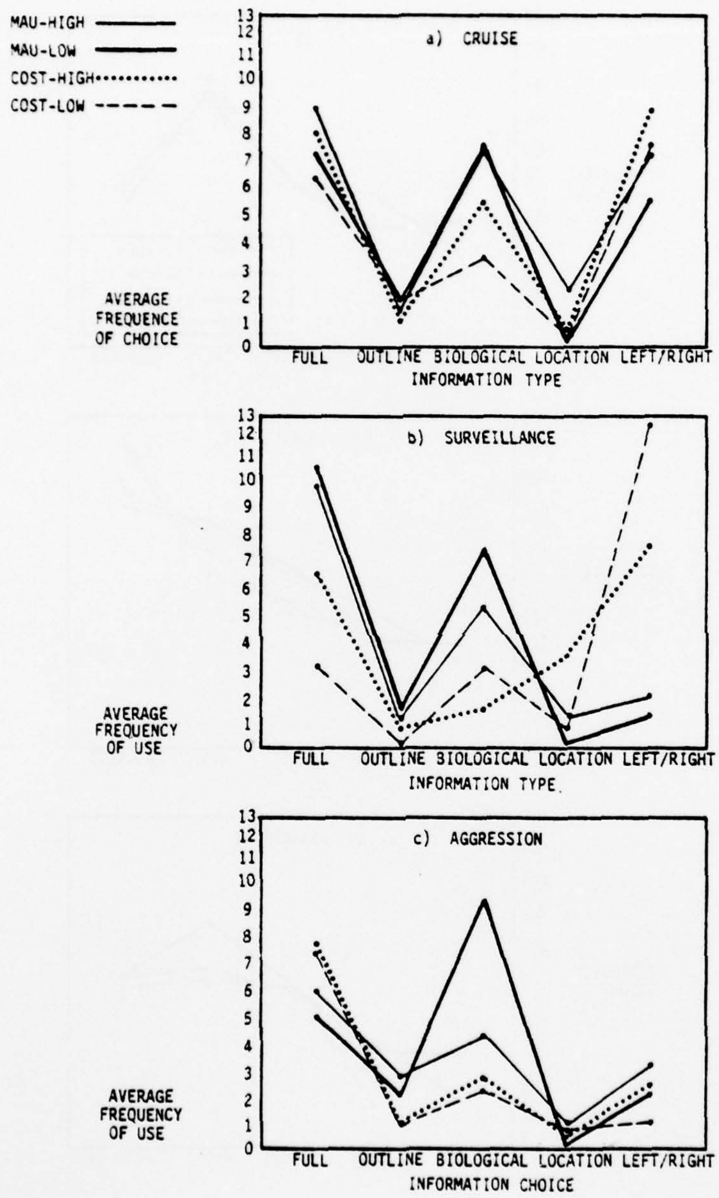


FIGURE 5-3.
INFORMATION CHOICE DISTRIBUTION AS A FUNCTION OF MODEL TYPE AND PERFORMANCE FOR a) CRUISE, b) SURVEILLANCE, AND c) AGGRESSION

The second phase, surveillance, shows a much wider variation of policy weights and information choice distributions. The large variation would be expected, since the surveillance phase is the most complex of the three phases, and would be expected to discriminate between decision makers and between models. Noticeable differences that cut across all phases are found with the cost and delay weights of the MAU model. These differences consistently discriminate between low and high performance subjects in all of the phases. The high scoring subjects placed a greater emphasis on cost and less emphasis on delay compared to the low-scoring group.

The final phase, aggression, is again a task low in complexity. No detection was present, and most information choices were of the first three forms--full, outline, and biological--as these afforded the most information for aggressive actions. For the most part, the policies and behaviors were closely bunched except for one outlying set of trials, that of the low scorers employing the MAU model. This group was also characterized by especially high cost expenditures, and low consistency.

It was expected that some decision makers would benefit more from the MAU model and some would be aided more by the cost-benefit model. The subjects were ranked according to the difference in gain scores achieved with the two models. For each subject, a gain score was defined at automated score minus the manual score. The difference between the MAU and cost-benefit gain scores then becomes a measure of the relative advantage (or disadvantage) of the MAU model compared to the cost-benefit model. Division of the subjects into MAU favored and cost-benefit favored groups did not reveal any significant behavioral differences. In fact, most of the difference was accountable by the difference in manual performance under the two models. The difference in gain scores correlated between .60 and .96 ($P < .05$) with the difference in manual scores. This indicates that

most of the model differences were simply due to differences in the quality of the original manual behavior upon which the models were trained.

5.5 Information Value

An advantage of the MAU model over the cost-benefit model was evident in information value computation. The marginal information value calculated for each source (see Section 2.4.2 for a description of this measure) was correlated with the actual score attained with each source. The correlation was found to be higher for the MAU model ($r = .55$, $P < .05$) and than for the cost-benefit model ($r = .37$, $P < .05$). When broken down by phase, the findings are similar, as shown in Figure 5-4. The correlations are somewhat higher for the slow conditions compared to the fast, as might be expected from the more deliberate behavior present in the slow conditions.

5.6 Subjective Responses

An interesting finding was the difference in subjective estimates of informative effectiveness between the manual and automatic conditions. In the manual conditions, a significant correlation was present between the score attained and the perceived information effectiveness ($r = .50$, $df = 14$, $P < .05$). In neither mode of automatic selection, however, did the correlation reach significance. It appears that the subjects were more aware of information quality in the manual information selection conditions.

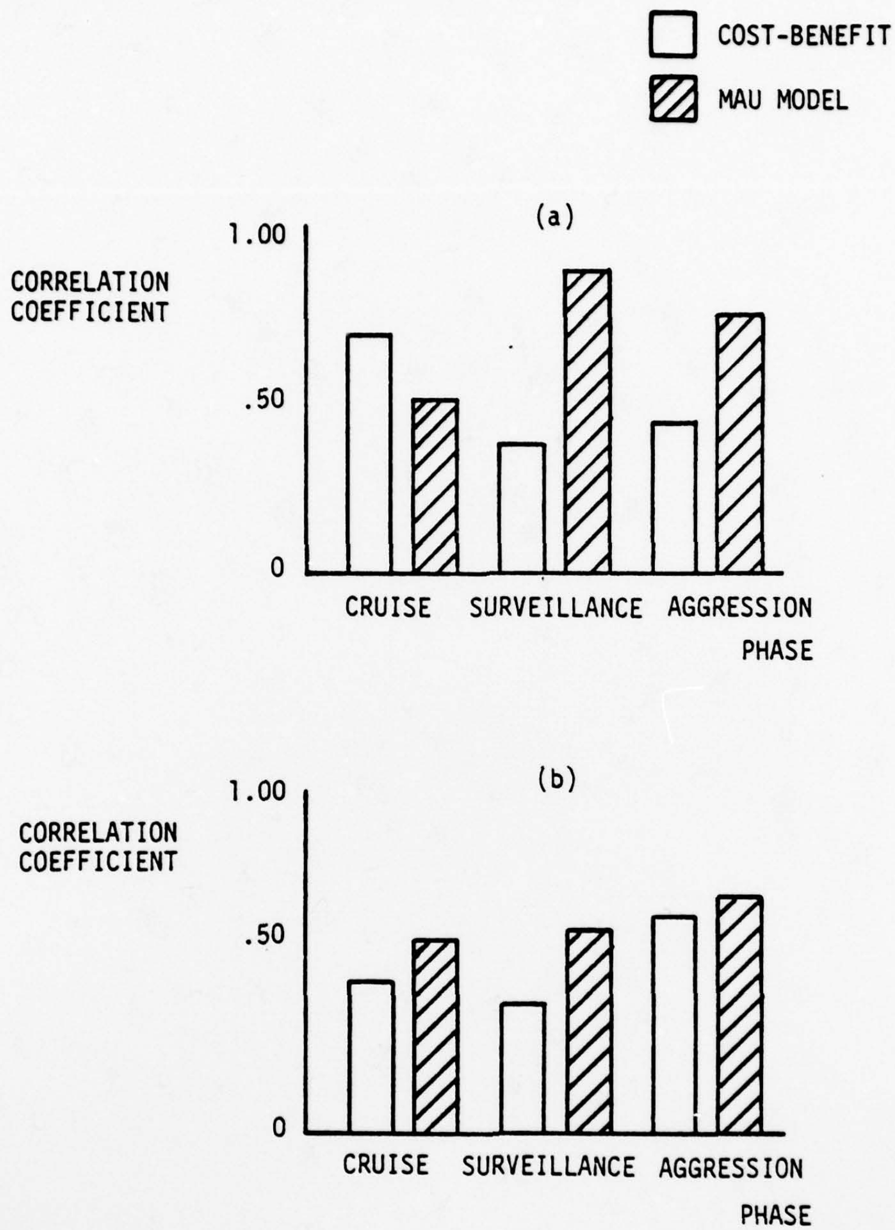


FIGURE 5-4.
CORRELATION OF INFORMATION VALUE ESTIMATE AND ACTUAL SCORE ATTAINED AS A FUNCTION OF PHASE IN (a) SLOW SPEED CONDITIONS AND (b) HIGH SPEED CONDITIONS

6. CONCLUSIONS AND RECOMMENDATIONS

The experimental study demonstrates the robustness of linear models for capturing information acquisition behavior. Two very different models were found to provide essentially equivalent performance in the advanced aircraft task simulation.

Significant differences between the models were seen in cost conservation. Surprisingly, the cost-benefit model resulted in more rapid resource depletion than the MAU model. This may have been due to the use of one additional adjustable factor in the MAU model compared to the cost-benefit model, and to the simpler and more rapid adjustment algorithm used with the MAU model.

Using either model, automated information management resulted in the classic reduction in noise or randomness of the unaided behavior. The variance of automated scores was significantly lower than that of the manual performance scores. Increased aiding with the adaptive technique is also possible. The probability estimation programs and attribute weights were both "frozen" during the experimental sessions. Dynamic estimation of outcome probabilities specific to each subject should improve the accuracy of the attribute level estimates and, in turn, result in more effective information selection. Similarly, allowing the attribute weights to adjust dynamically with the task demands should improve performance.

The influences of task load in the form of speed and choice complexity were evident in the form of altered policies, reduced consistency with load, and decreased performance. The differences were not as dramatic as anticipated, and appear to require greater ranges of load to be of major impact. More continuous variation of loading also appears necessary to

determine the functional relationships required for incorporating load factors into the decision model.

Information value estimates using the two models were found to be useful. Consistent with the other findings, information value estimates obtained using the MAU model were significantly more predictive of actual scores attained than were estimates made using the cost-benefit model. The estimates were also more predictive in the slow speed, and presumably more deliberate conditions. A rough evaluation of a given information system component thus appears to be possible by integrating the calculated situation-specific information value contributions over the expected distribution of situations.

A finding of potential importance concerns the level of awareness of aiding. Correlations of the perceived information effectiveness (elicited prior to each session) and the actual score attained were moderately strong for manual information selection but not significant for automated selection. This may indicate that in the active (manual) information selection mode, the operator can easily discriminate good decision performance, while in the more passive automated modes, the operator is not as aware of information quality. Additional research is needed to determine the form of feedback necessary for awareness of aiding quality in both partially and fully automated systems.

7. EXAMPLE APPLICATION: F-14 THREAT INTERCEPT OPERATIONS

7.1 Background

Many of the information management aids developed in this program may be illustrated in the context of F-14 threat intercept operations. Perceptronics has recently investigated the possibility of developing tactical decision aids to interface with the F-14 AWG-9 weapon system. This work was performed under contract to Naval Air Development Center (Madni, Steeb and Freedy, 1979), and offers an excellent opportunity to apply many of the information management techniques derived here. The weapon system of the F-14 is quite sophisticated. It consists of the AWG-9 Airborne Weapon Control System (AWCS), the LAU-934 missile launchers and the AIM-54A Phoenix missile. The AWG-9, in addition to launching the Phoenix missile, can launch other modern naval air-to-air weapons, including Sparrow and Sidewinder missiles and can direct firing of the M-61 Vulcan 20 mm cannon. The system has the capability to control this array of weapons in any tactical situation, enabling the F-14 to fulfull its mission of providing air superiority and fleet air defense. The AWG-9 utilizes a high-power pulse doppler radar with a planar array antenna which provides a 'look down' capability that enables it to pick out moving targets (such as low flying missiles and aircraft) from ground or sea clutter that normally obscures targets in a conventional radar. In addition, the system incorporates a digital computer, controls and displays, and an infrared subsystem that provides an independent search and track sensor.

7.2 Problem Area

An area of critical importance is that of achieving a launch acquisition region (LAR) on each target. A LAR is a volume of space where a missile can be launched with some expectation of successful target intercept. A

LAR is characterized by an infinite number of launch points. It is bounded by maximum range, minimum range and the doppler exclusion region. Maximum Range depends on (1) how far the missile can see (target detection capability) and (2) how far the missile can fly (depends on the missile's maximum time of flight). Minimum Range depends on (1) minimum missile guidance time; (2) aircraft antenna gimbal limit; (3) missile antenna gimbal limit; (4) missile-to-target intercept geometry and (5) safety considerations. Doppler Exclusion Region results from the fact that doppler frequency of target return close to that of main lobe clutter (MLC) causes regions around the target in which missiles cannot be launched or, subsequently, guided. When target tracks appear on the Target Information Display (TID) they are sometimes accompanied with LARs on those targets and sometimes not. A LAR on a given target indicates that that target is fair game from that point on. If a situation arises where some of the targets tracks are accompanied by LARs while others are not, then certain situation-specific decisions are warranted. The present level of aiding indicates when the F-14 will enter a LAR or exit a LAR. It makes no attempt to inform the aircrew why they don't have a LAR on a given target, how to get a LAR if the present course will not intersect it or how to stay in the LAR for a sufficient period of time. These obvious deficiencies coupled with upgraded resources in terms of computer memory and processing make the LAR entry problem a rich framework for illustrating the need for automated information analysis and management programs.

7.3 LAR Aiding System Concept

An information management and decision aiding system must be designed with a view to answering in real-time the following major questions for the flight officer.

(1) What am I up against? (Situation assessment)

(2) Can I do anything about it? (Acquisition of information and determination of alternative maneuvers)

(3) Specifically, what should I do? (Maneuver selection)

The answers to these questions form the crux of the aiding system. The answer to the first question requires a predictive assessment of the impending threat. This assessment includes all hostile targets with and those without LARs. The answer to the second question requires a diagnosis of the situation, i.e., why don't I have a LAR, what information can I gain and what actions should I take to acquire one. The answer to the third question requires an estimation of the consequences of each feasible option and determining the optimum choice based on the degree to which the outcomes associated with each action attain the desired objectives. As each question is answered the partial information may be conveyed to the flight officer to allow interaction with the system and also have a better understanding of the problem enroute to the final option recommendation. The aiding sequence system concept is illustrated in Figure 7-1.

Close correspondences are present between each of the above stages and the processes described in Section 2.3. The situation assessment block in Figure 7-1 is equivalent to the mission situation inputs of Figure 2-2. Here the importance weights are defined for each attribute and the event probabilities input. The alternative generation block corresponds to the list of available actions phase of Figure 2-4. The system constraint block is a special expansion of the information value program. The constraint check acts as a filter, culling out those options which exceed a system constraint: radar look angle, range, G-loading, etc. The next block, consequence estimation, is the same as attribute level estimation. Probability and outcome level computations are made from the sensed conditions. The final function in Figure 7-1 is that of option evaluation.

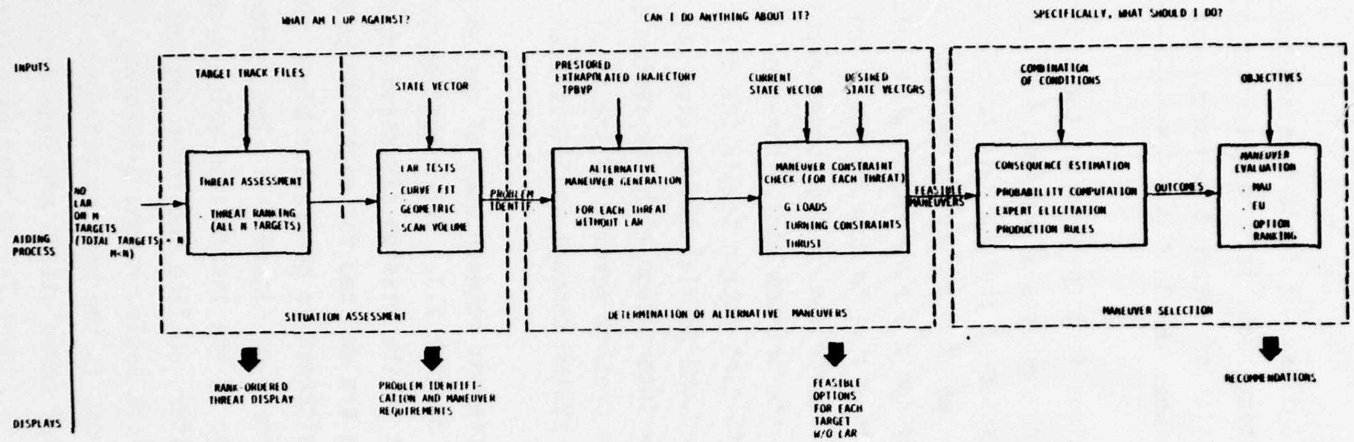


FIGURE 7-1.
AIDING SEQUENCE SYSTEM CONCEPT

This is identical to the MAU evaluation used in the information evaluation program. The options are ranked using a situation-specific weighting of attributes. The weights are determined either off-line, through direct elicitation or on-line, adaptively.

The example problem selected to illustrate the application of the information management program is that of multiple threats sighted and identified during a mission. Launch acquisition reasons (LARS) are acquired only on a subset of the targets and information is available for determining the reasons for absence of a LAR. Finally, sufficient time is present for generating and evaluating maneuvers for acquiring the additional LARS. This time span is anticipated to be on the order of 20 to 60 seconds.

7.4 Decision Aid Configuration

7.4.1 *Problem Identification*. The absence of a LAR on an identified target may be due to (1) the lack of vehicle capability to perform the required maneuver, (2) the absence of a LAR intercept, or (3) the incompatibility of continuous radar illumination with the projected fighter path. Each of these three problems may be identified using information available to the AWG-9 program. Tests for curve fit parameters, geometric checks for LAR intercepts, and radar scan volume tests can be used to pinpoint the problem.

7.4.2 Problem Display. Display of the identified LAR problem may be accomplished on the target information display. Vehicle range capability, LAR intercept discrepancy and radar scan volume constraint relative to actual target azimuth and elevation angles may each be shown along with the predicted aircraft positions.

If sufficient time is available, the problem may also be displayed textually. This allows display of exact intercept coordinates and predicted times of flight.

7.4.3 Threat Evaluation Computation. Threat evaluation is done by decomposing the threat into its features, assigning weights to each feature and aggregating the feature levels times weight across the features to come up with an overall evaluation of threat. Features that characterize threat are: target time of flight to intercept, target maneuverability and target weapon capability. Target time of flight ranges from small, medium and large depending on discrete ranges of the TOF: $0 < TOF < \varepsilon$, $\varepsilon < TOF < T$, and $TOF > T$, respectively. Target maneuverability ranges from high to medium to low. Target weapon capability can also be described by high, medium and low. The weights assigned to each of these features is keyed to the tactical situation, i.e., heavily outnumered (defensive positive), evenly matched, under matched (offensive posture). The targets are rank ordered from maximum threat to minimum threat on the basis of pattern recognition of the threat features.

7.4.4 Maneuver Assessment. The candidate information acquisition and system status change options must be tested for feasibility prior to evaluation. Checks have to be made to determine if constraints are exceeded in the g-loading, thrust, turning requirements, time to maneuver, sensor range or some other aerodynamic, sensor or environmental parameters or if aircraft performance is stressed to its limits for extended durations. This initial check acts as a filtering process to reduce the number of options actually evaluated to those that are physically achievable with a reasonable change of success.

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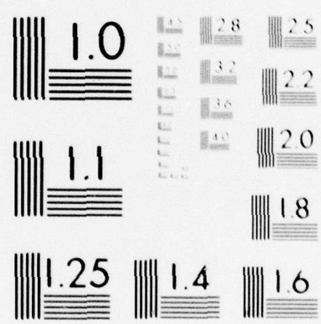
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7.4.5 LAR Entry Decision Criteria. The choice of information acquisition and subsequent LAR entry maneuver must be made on the basis of key mission objectives. The major objectives are protection of the carrier, avoiding own losses, and maximizing tactical gains. Each of these objectives may be broken down into measurable attributes, which correspond to the degree of attainment of the objective. A preliminary set of attributes is defined below:

OBJECTIVE	ATTRIBUTES
Minimize threat to carrier	Degree of carrier damage
Maximize tactical gain	Fighter-equivalents destroyed
Minimize own losses	Number of missiles fired
	Amount of fuel expended
	Degree of damage sustained

Data available to the decision aiding program are:

(1) Directly sensed information concerning the environmental state (weather, terrain, ECM, target track).
(2) The vehicle state (velocity, fuel).
(3) The information system characteristics (radar mode, target size switch setting, scan volume).
(4) Tactical data (characteristics of own and enemy aircraft maneuverability, on-board sensors and weapons; information about the operations area).
(5) Action alternative (control responses, weapon deployment).

The importance weights for each of the attributes (the k_i in equation 2-4) must be estimated and input to the system prior to decision aid operation. Sets of importance weights for each distinct mission phase or situation will be estimated by the command group. The estimation may be made

adaptively, using a computer simulation of the task, or may entail a direct elicitation (see Steeb, Davis, Alperovitch and Freedy, 1978, for a description of direct elicitation techniques). If conflicts occur between the estimators, a resolution procedure such as Delphi or nominal groups (see Gustafson, et al., 1973, for a discussion of these techniques) may be used to arrive at a useful consensus.

A simplified decision tree for the LAR acquisition decision is shown in Figure 7-2. The first branching of the tree is the maneuver option open to the aircrew. The subsequent uncertain events are whenever the missing LAR corresponds to a high or low threat target. Additional events deal with whether the target is destroyed, operational or the aircrew's own craft is lost. The probability of occurrence of each of these events depend on the actions and events leading up to the event along with the survival conditions.

With these considerations in mind, the decision tree shown in Figure 7-2 has been developed for the hypothetical scenario when N target tracks are displayed on the TID, but only M of them have LARS (M < N). All threat and preliminary maneuver assessments have been performed. The first branching shows the options identified to be feasible. If the first information acquisition option is selected, either N LARS, less than N LARS, or a new threat will occur. The missing LARS may in turn be low or high threat, resulting in the avoidance or sustanining of a hit by the operator's own craft. If a hit is avoided, the flight officer selects one of the targets for launch and either scores a hit, misses, or sustains a hit. The final branching deals with the damage sustained by the target. Two categories are shown: target destroyed and target operational.

Each of the events (denoted by a circle at the tree branching in the diagram) has an associated probability of occurrence. The probability is a function of the actions and events leading to that point and to the

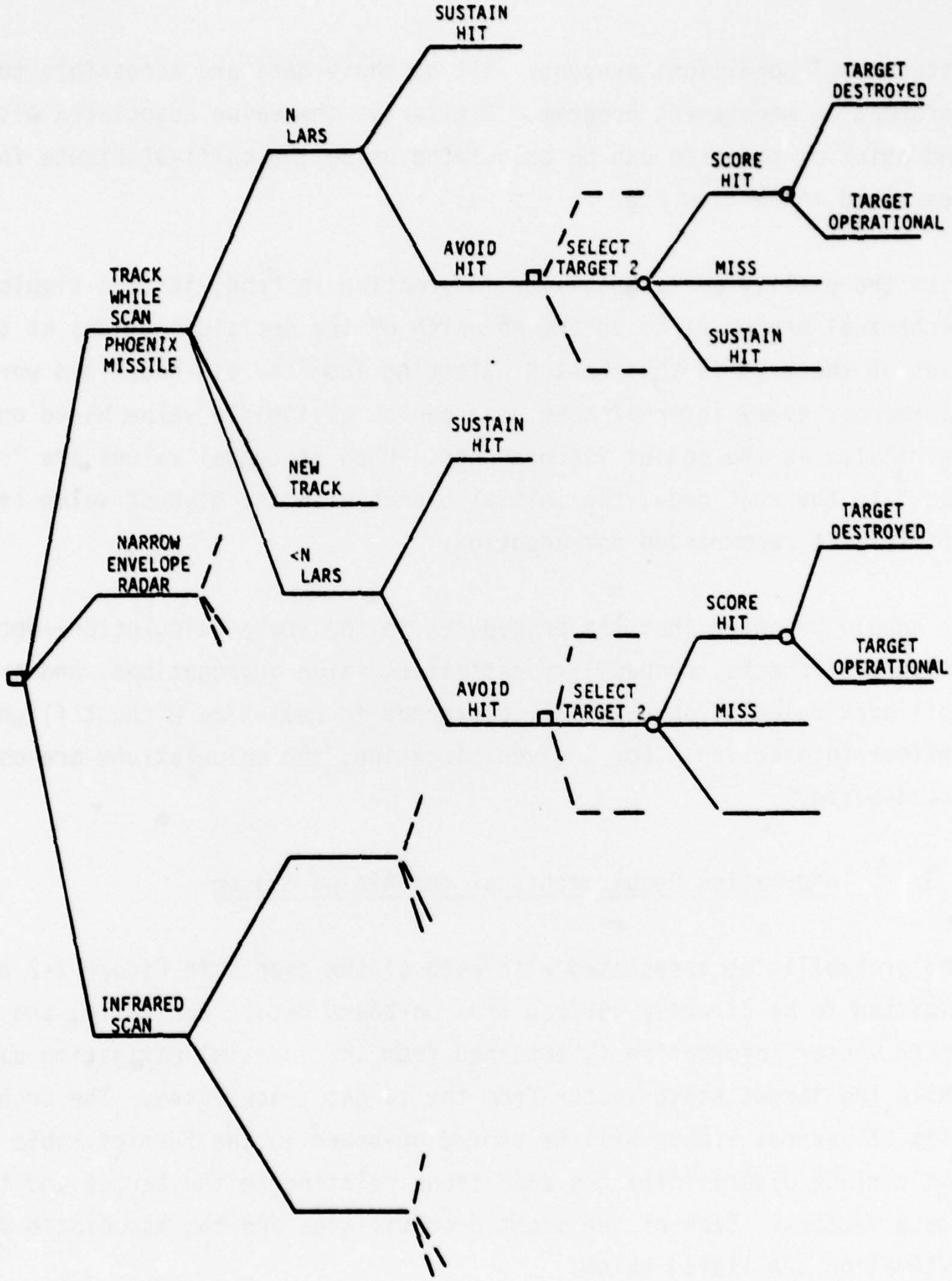

FIGURE 7-2.
LAR ACQUISITION DECISION TREE

situational conditions present. All of these data are accessible to the information management program. Similarly, the value associated with each end point of the tree can be calculated using the multi-attribute form described in Section 2.3.

With the utility and probability information in hand, it is a simple mechanical procedure to determine which of the decision options at the root of the tree is the "best." Starting from the tip nodes and working backwards, every internal tree node can be assigned a value based on the attributes at the end of its branches. When the nodal values are "rolled-back" to the root node, the initial branch with the highest value (expected utility) is recommended for adoption.

It should be noted that the procedures in the above calculation--option constraint checks, probability estimates, value aggregations, and tree-roll back calculations--are all performed in real-time without flight officer interaction. For a given situation, the calculations are essentially "hard-wired."

7.5 Information Requirements of the Aiding System

The probabilities associated with each of the events in Figure 7-2 are expected to be directly derived from on-board data. Generally, the F-14 state vector information is obtained from the inertial navigation data while the target state vector from the target track files. The probabilities of various events will be stored on-board in the form of table lookup for various discrimininating conditions relating to the target and the F-14 state vectors. Each of the event probabilities and the associated data for estimation are listed below:

P_1: Probability that less than N LARS after information acquisition; this is a function of uncertainty in knowledge of true target and F-14 state vectors and the complexity of the required information acquisition option.

P_2: Probability of N LARS after information acquisition; this is a function of uncertainty in knowledge of true target and F-14 state vectors.

P_3: Probability of new target track appearing on the target information display without a LAR.

P_s: Probability of sustaining a hit; this is a function of target type, target capability, intercept geometry, V_c, own resources available.

P_a: Probability of avoiding a hit = $1 - P_s$.

P_{ht}: Probability that target with no LAR is a high threat; this is a function of target type, target capability V_c, time to acquire LAR, decreasing aspect angle, vehicle capability, etc.

P_{lt}: Probability that target with no LAR is a low threat = $1 - P_{ht}$.

P_{sh}: Probability of scoring a hit on target; this is a function of fuze type, warhead, vehicle capability, target vulnerability, selected missile type, intercept geometry, location within target LAR (if probabilistic information available on-board), etc.

P_m: Probability of missing target; this is a function of missile range capability, state vector errors, location within LAR, etc.

7.6 Feedback Options

Display of recommendations from the decision aids described above come at a number of points in the decision aiding circle. Figure 7-1, presented in Section 7.3, summarizes the inputs, decision aiding algorithms, and feedback displays for the overall system. The first display is that of a rank-ordering of targets based on the threat they pose. The next display is that of a LAR acquisition problem and its magnitude for each of the target tracks on the TID without LARS. Depending on the type of problem and time available, either graphic or textual messages are displayed on the TID.

The succeeding display is the set of feasible radar and maneuvers options. This is a listing output by the system status and maneuver assessment program. The options are shown both in list form and, if possible, on the target track. If time is severely limited, the display may be suppressed.

The final and most important display is that of the recommended information acquisition and maneuver options. This is output from the decision evaluation program. The recommended radar parameters can be shown on the TID. Also a ranking of the remaining options can be listed.

It should be noted that the display of aiding information is driven by the situation and time stress. Under extreme time stress, only the threat and system status assessments may be possible. With great time, the full set of displays may be activated.

The sequence of aiding is closely related to that described in Section 2.3. Each source of information is analyzed according to its potential usefulness along a set of key attributes. The information usefulness is traced through the action decisions. Policy weights for the various attributes

are determined for each distinct mission situation and each decision maker. Finally, the system can provide diagnostic information, make information and action recommendations, and establish a basis for automated display management.

8. REFERENCES

Anderson, N.H. Primary Effects in Personality Impression Using a Generalized Order Effect Paradigm. Journal of Personality and Social Psychology, 1965, pp. 1-9.

Anderson, N.H. and Shanteau, J.C. Information Integration in Risky Decision Making. Journal of Experimental Psychology, 1970, 84:441-51.

Baron, S., and Levison, W.H. An Optimal Control Methodology for Analyzing the Effects of Display Parameters on Performance and Workload in Manual Flight Control, IEEE Trans. Syst. Man Cybern., 1975, SMC-5:423-430.

Brown, I.D. Criticisms of Time-Sharing Techniques for the Measurement of Perceptual-Motor Difficulty, Paper to International Congress of Applied Psychology, Amsterdam, 1968.

Chu, Y. and Rouse, W.B. Adaptive Allocation of Decision Making Responsibility between Human and Computer in Multi-task Situations. IEEE Trans. Syst. Man Cybern., December 1979, SMC-9(12).

Edwards, W. Probabilistic Information Processing System for Diagnosis and Action Selection. In J. Spiegel and D. Walker (Eds.) Information System Sciences, Proceedings of the Second Congress (Washington, D.C.) Spartan Books, Inc. 1965, pp. 141-155.

Edwards, W. and Guttentag, M. Experiments and Evaluations: A Re-Examination. In C. Bennett and A. Lumsdaine (Eds.) Experiments and Evaluations. New York: Academic Press, 1975.

Einhorn, H. and Hogarth, R. Unit Weighting Schemes for Decision Making. Organizational Behavior and Human Performance, 1975, 13:171-192.

Emery, J.C. Organizational Planning and Control Systems, New York: Macmillan Company, 1969.

Engstrom, K.D. and Rouse, W.B. Telling a Computer How a Human Has Allocated His Attention Between Control and Monitoring Tasks. Proceedings of the Annual Conference of Manual Control, 1977.

Felson, J. Artificial Intelligence Techniques Applied to Reduction of Uncertainty in Decision Analysis Through Learning. Operational Research Quarterly, 1975, 26(3):581-598.

Fischer, G.W. Multi-Dimensional Value Assessment for Decision Making. Engineering Psychology Laboratory, University of Michigan, Technical Report 037230-2-T, 1972.

Gardiner, P.C. The Application of Decision Technology in Monte Carlo Simulation to Multiple Objective Public Policy Decision Making: A Case Study in California Coastal Zone Management. Unpublished Ph.D. Dissertation, Center for Urban Affairs, University of California, 1974.

Greening, C.P. Analysis of Crew/Cockpit Models for Advanced Aircraft, Naval Weapons Center Technical Publication 6020, February 1978.

Gustafson, D. "A Comparative Study of Differences in Subjective Liklihood Estimates Made by Individuals, Interacting Groups, Delphi Groups, and Nominal Groups," Organizational Behavior and Human Performance 9, 1973.

Hart, S.G. Content, Symbology and Format of Cockpit Display of Traffic Information: Pilot Opinion, in Proceedings of the Fifteenth Annual Conference on Manual Control (Payton, Ohio) March 1979.

Johansen, G. Preview of Man-Vehicle Control Session in Monitoring Behavior and Supervisory Control, T.B. Sheridan and G. Johannsen (Eds.) NATO Conference Series, III Human Factors, New York: Plenum Press, 1976, I:3-12.

Johannsen, G. Position Paper on Metal Workload, paper presented in NATO Workshop on Methods to Assess Workload, Greece, 1977.

Johns, D.W. A Concept of Operator Workload in Manual Vehicle Operations, Research Institute Human Engineering Report Number 14, Mechenheim, Germany, December 1973.

Keeney, R.L. and Raiffa, H. Decision Analysis with Multiple on Conflicting Objectives, Preference, and Value Trade-Offs. New York: Wiley, 1975.

Keeney, R.L. and Sicherman, A. An Interactive Program for Assessing and Analyzing Preferences Concerning Multiple Objectives. International Institute for Applied Systems Analysis Report RM-75-12 (Laxenburg, Austria) April 1975.

Kelly, C.R. and Wargo, M.J. "Cross-Adaptive Operator Loading Tasks," Human Factors, October 1976, 9(5):394-404.

Levine, J.M. and Samet, M.F. Information Seeking With Multiple Sources of Conflicting and Unreliable Information. Human Factors, 1973, 15(4): 407-419.

Macrimmon, K.R. and Taylor, R.N. Decision Making and Problem Solving Processes. In M.D. Dunnett (Ed.) Handbook of Industrial and Organizational Psychology. New York: Rand McNally, 1972.

Madni, A., Steeb, R. and Freedy, A. Perceptronics, Inc. (Woodland Hills, California) Computer Based Tactical Decision Aids For The F-14 AWG-9 Weapon System. May 1979, Technical Report P-79-102-1979.

Marschak, J. Economics of Information Systems. Journal of the American Statistical Association, March 1971, 66(333):192-219.

Marschak, J. The Payoff-Relevant Description of States and Acts. Econometric, October 1963, 21(4):719-725.

McKendry, J.M., Enderwick, T.P. and Harrison, P.C. A Subjective Value Approach to Information Utility. Human Factors, 1971, 13(6):503-509.

Miller, J.G. Sensory Overloading in Psychophysiological Aspects of Space Flight, B.E. Flaherty (Ed.) Columbia University Press, 1961.

Nilsson, N.J. Learning Machines. San Francisco: McGraw-Hill, 1965.

Pitz, G.F. Information Seeking When Available Information Is Limited. Journal of Experimental Psychology, 1968, 76(1):25-34.

Raiffa, H. Preferences for Multi-Attributed Alternatives. Rand Corporation (Santa Monica, California) Memorandum RM-5868-DOT/RC, April 1969.

Rolfe, J.M. The Secondary Task as a Measure of Mental Load in Measurement of Man at Work, W.T. Singleton, J.G. Fox, and D. Whitfield (Eds.) Taylor and Francis, LTD. London, 1973.

Rouse, W.B. Human Interaction with an Intelligent Computer in Multi-Task Situations. Proceedings Annual Conference on Manual Control, NASA Ames Research Center, May 1975.

Rouse, W.B. and Gopher, D. Estimation and Control Theory: Application to Modeling Human Behavior. Human Factors, August 1977, 19(4):315-330.

Samet, M.G. Automated Information Selection and Pacing in Proceedings of the 1978 International Conference on Cybernetics and Society. Japan, November 1978. New York: IEEE 1978:1412-1420.

Samet, M.G., Weltman, G., and Davis, K.B. Application of Adaptive Models to Information Selection in C3 Systems, Perceptronics Inc. (Woodland Hills, California), Technical Report PTR-1033-76-12, December 1976, Chapter 2.

Sanders, M.G. Simmons, R.R., Hofman, M.A. and DeBonis, J.N. Visual Workload of the CoPilot/Navigator During Terrain Flight, in Proceedings of the Annual Meeting of Human Factors Society, 1977:262-266.

Shanteau, J.C. An Additive Model for Sequential Decision Making. Journal of Experimental Psychology, 1970:181-191.

Sheridan, B. Toward a Model of Supervisory Control. T.B. Sheridan and G. Johanssen, (Eds.), Monitoring Behavioral and Supervisory Control, New York, Plenum Press, 1976.

Slovic, P., Fischoff, B. and Lichtenstein, S. Behavioral Decision Theory. Annual Review of Psychology, 1977, 28:1-39.

Snapper, K.J. and Peterson, C.R. Information Seeking and Data Diagnosticity. Journal of Experimental Psychology, 1971, 87:429-433.

Spady, A.A. Preliminary Report on Airline Pilot Scan Patterns During ILS Approaches, in Proceedings of the Aircraft Safety and Operating Problems Conference, NASA Report SP-416, October 1976.

Steeb, R. and Chu, Y. Approaches for Supervisory Management of Information in Automated Airborne Systems, Proceedings of 15th Annual Conference on Manual Control (Dayton, Ohio) March 1979.

Steeb, R. and Freedy, A. Man-Machine Interaction in Adaptive Remote Systems, Proceedings of the IEEE Conference on Cybernetics and Society, (Washington, D.C.) November 1-3, 1976.

Steeb, R., Chen, K. and Freedy, A. Adaptive Estimation of Information Values in Continuous Decision Making and Control of Remotely Piloted Vehicles. Perceptronics Technical Report PATR-1037-77-8. (Woodland Hills, California) August 1977.

Steeb, R., Davis, K., Alperovitch, Y., and Freedy, A. Adaptive Estimation of Information Values in Continuous Decision Making and Control of Advanced Aircraft. Perceptronics Technical Report 1037-78-12. (Woodland Hills, California) December 1978.

Van Cott, H.P. and Warrick, M.J. Man As A System Component, in Human Engineering Guide to Equipment Design, H.P. Van Cott, and R.G. Kinkade, (Eds.) U.S.G.P.O., 1972, Chapter 2.

Van Gigch, J.P. A Process Computer's Contribution to the Reduction of Mental Effort and to the Handling of Systems Malfunction. International Journal of Man-Machine Studies, 1971, 3(3):201-218.

Von Winterfeldt, D. An Overview, Integration, and Evaluation of Utility Theory for Decision Analysis. Social Science Research Institute, University of Southern California (Los Angeles, California), Research Report 75-9, August 1975.

Wendt, D. Value of Information for Decisions. Journal of Mathematical Psychology, 1969, 6:430-443.

Whittemore, J. and Yovits, M.C. A Generalized Conceptual Flow for the Analysis and Flow of Information. Journal of the American Society for Information Science, May-June 1973.

Wickens, C.D., Isreal, J. and Donchin, E. The Event Related Cortical Potential as an Index of Task Workload, Proceedings of Annual Meeting of Human Factors Society (San Francisco, California), October 1977.

APPENDIX A
SYSTEM APPLICATION GUIDELINES

1. SYSTEM APPLICATION GUIDELINES

1.1 Introduction

The three years of research on this program have resulted in a number of analytic and experimental findings. This section is a compilation of these findings arranged by topical area. The intent is to provide a set of guidelines to assist designers of upcoming systems and to provide a framework within which subsequent findings can be inserted.

1.2 Application Areas

We have found that user-based programs for information evaluation and management have primary application in systems with (1) complex (multi-attributed) information choices, (2) costly communications, (3) extensive machine autonomy, and (4) subjective factors. Among the types of systems sharing these characteristics are advanced aircraft information systems, remote manipulators, remotely piloted vehicles, and biomedical monitoring systems.

The area showing the greatest immediate application is that of advanced tactical aircraft. These aircraft already have high information loads, substantial amounts of automation, and critical decision-making requirements.

1.3 Catagories of Aiding

Aiding provided by the information value programs may take the form of problem recognition, situation diagnosis, option selection, and system evaluation.

Problem Recognition. This aspect of the decision process involves the monitoring of an ongoing action on a set of descriptive dimensions, comparing the set against acceptable limits, and determining that the action is still appropriate to the situation. Outcomes of these processes either initiate a new action, or modify an ongoing action.

Problem recognition is a key function in airborne tactical operations. Aircraft may be programmed to follow a course unless special circumstances arise. Response maneuvers or transfer of control to the supervisory operator may be specified by the multi-attribute decision model. Again, trade-offs between communication costs, potential losses, operator loading, and other factors are made by the model. This function unburdens the operator of repeatedly interrogating the system as to its status.

Situation Diagnosis. For effective decision making and control functions, the operator must accurately assess and integrate the probability of occurrance of events. Among these estimates are judgments regarding likelihoods of obstacles, detection of communications, possibility of visibility loss, etc.

The decision model performs many of the probability aggregation functions normally required of the operator--frequency tabulations, probability update calculations, etc. The program performs these calculations more rapidly, reliably and accurately than is possible manually. The operator of course, may still provide inputs for the probability programs in the form of single item prior and conditional probabilities.

Option Selection. The options open to the decision maker are information to acquire and actions to select. These options are interdependent. The value of information is due to its impact on the subsequent action decision.

Each of these choices, information acquisition and action selection, is tied to maximization of overall expected gain or utility. For the operator, simultaneous consideration of multiple alternatives portrayed against multiple criteria quickly becomes too complex for easy resolution. Computer based aggregation of the various factors is typically faster and more consistent than is possible by the operator. The information value model can be used directly for management of information. The multi-attribute utility model represents the policy of the specific user, it has access to the factors characterizing each information choice, and it can be linked to the onboard information control system. The model can be configured to automatically scan the available information source, select the immediately most useful source, and display it to the operator.

Information Value Analysis. The various linear models developed in this program provide a framework for determining the value of an information system component or configuration. Two main types of evaluation are possible: additive and marginal. The additive contribution is simply the weighted aggregation of attributes for a given information source summed across the expected distribution of situations. This evaluation form is suited for information sources of distinct function--system faults, radar, communications, etc.

For comparisons of information value within an information type, such as variations in the power and envelope of a radar scan, the marginal contribution is a useful measure. This is the decision-by-decision sum of the marginal contributions of a source compared to the next most highly valued option. The intent is to determine if the source in question makes a justifiable additional benefit beyond the existing source set. The marginal information value was found to correlate strongly with the actual scores attributable to each source.

Implications for Choice of Aiding Level. The choice of the form of aiding to be used in a given situation depends on the time stress present, the complexity of the decisions, the criticality of the outcomes, and the amount of pre-analysis possible. As the time stress and the decision complexity decrease, the usefulness of automated option selection decreases. When the operator has sufficient time to consider only a few low-dimensionality choices, the situation diagnosis form of aiding appears most useful, providing the operator with data on the implications of the choices. The first and second years of the study demonstrated that the more complex model-based recommendation of choices or actual replacement of the operator are most useful in situations of high time stress, decision complexity and extensive model training (Steeb, et al, 1978, 1979). Aiding in the form of system evaluation is most effective as a means of designing information system components for specified mission requirements and for adjusting the system characteristics during a mission.

1.4 Model Structure

A number of types of models are possible for capturing an operator's information-seeking behavior. Among the more prominent are (1) cue regression models, (2) utility models, (3) queueing models, and (4) game-theoretic formulations.

Cue Regression. Cue regression is the simplest of the group. In cue regression, a single linear model aggregates a variety of independent factors to predict behavior. Each factor is scaled and weighted according to importance. The influences of the individual factors are then combined additively, multiplicatively, or in some other fashion to arrive at an evaluation of each information choice. The formulation for the simple additive case is:

$$R = \sum_i W_i S_i + C$$

Where R is an interval scaled performance response, S_i is the stimulus level on dimension i, W_i is the regression weight, and C is an optional scaling constant. The advantages of the cue regression approach are its simplicity and robustness. Virtually any available predictive factors can be used, such as information content, data perishability, channel quality, and operator load. In fact, the ensuing action decision does not even have to be represented. The terminal decision is simply assumed to drive the operator's information seeking behavior. Also, the linear model has been shown to be robust to inaccuracies in modeling, and highly predictive of behavior in a variety of situations (Dawes and Corrigan, 1974; Slovik, Fischhoff, and Lichtenstein, 1977). This model is most useful in situations were the relationships between the cues and the outcomes of the action decision are not well-defined or where a minimum of modeling effort is justified.

Multi-Attribute Utility (MAU) Models. The MAU models make the information seeking process more goal directed, normative and axiomatic. Instead of simply attempting to predict behavior on the basis of a set of independent features, the utility models tie the information decisions directly to the ensuing action decisions. The value of obtaining information is determined by calculating its impact on the expected utility of the subsequent action decision. The information is assumed to change the probability distributions of the consequence sets and, in turn, to revise the expected values of the alternative actions. Nevertheless, the form of the model is again a linear additive rule. The utility of an action is considered to be an aggregate of many possible outcomes, each expressed along a set of attributes:

$$EU\ (a_k) = \sum_{\substack{\text{states}\\ h}} P(z_h) \sum_{\substack{\text{attributes}\\ i}} U_i\ (a_k, z_h)$$

Where EU (a_k) is the expected utility of action k, $P(z_h)$ is the probability of state z_h occurring, and U_i (a_k, z_h) is the utility function over the i^{th} attribute associated with state h and action k. The formulation is the result of several key simplifying assumptions. The decision maker is assumed to be risk neutral, so that indifference is present between the expectation across a set of uncertain outcomes and the uncertain outcomes themselves. This allows the probabilities to be entered as simple coefficients. Also, the attributes are assumed to satisfy additive independence, allowing the linear additive form of aggregation. Tests for compliance with these assumptions can be found in V. Winterfeldt (1975) or Keeney and Raiffa (1976).

The impact of a message or item of data is to change the probability distribution of the states z_h. Once the message is received, a maximum utility action $a^*(y)$ can be identified. The expected utility of selecting an information source S then becomes:

$$EU\ (S) = \sum_{\substack{\text{messages}\\ y}} \sum_{\substack{\text{states}\\ z}} P(z_h)\ P(y|z_h)\ u(a^*(y), z_h)$$

Here $u(a^*(y), z_h)$ is the utility of taking action $a^*(y)$ given that state z_h occurs. The utility function is again multi-attributed, but for simplicity $u(a^*(y), z_h)$ is portrayed as having already been aggregated across the various dimensions.

This type of analysis is suited for highly structured tasks. Not only must the possible states, messages, actions, and outcomes be specifiable,

but the prior state probabilities and the conditional probabilities characterizing the information system must be derivable.

Queueing Models. The cue regression and multi-attribute utility models are well suited to discrete, event-driven decisions, but are not designed to model the many continuous behaviors present in monitoring, tracking, etc. Many of these continuous stochastic processes can be modeled by embedding the multi-attribute decision model in a queueing model. Here the time distributions of processes such as system faults, course errors and energy management losses are known, and a queue of potential messages or sampling options are present. The queueing model provides an estimate of the buildup in uncertainty regarding a given process. The multi-attribute decision model is then incorporated as a criterion function in the queueing model.

The queueing framework of the multi-process system assumes that the time distributions of information message arrival and service times are known. With the service discipline specified, the queueing model would predict steady-state system characteristics such as average delay time, throughput, utilization and server occupancy (fraction of time the server is occupied by the message processing). The queueing model is also capable of modeling multiple display/multiple operator situations.

Game Theory Models. The final type of model, the game theoretic approach, assumes the presence of an adversary response to the information seeking decision. Minimax criteria and dynamic programming techniques may be used in this type of situation, but quickly become intractable in situations of any complexity. While the cue regression, MAU and queueing models normally assume a benign environment, factors for adversary response can be included in the criterion functions. For example, the second and third year studies included a linear factor for likelihood of damage due

to detection of ones' own aircraft. This modified linear model is much easier to deal with than the true game-theoretic approaches.

1.5 Factor Choice

The choice of attributes making up the criterion function of the cue regression, MAU or queueing models has been found to be an extremely important process. The attributes represent the constituent effects of the information choices (and the action choices in the MAU and cost-benefit models). The effects will be weighted and aggregated together to arrive at an overall evaluation of an outcome.

Necessary Attribute Characteristics. Desirable characteristics of an attribute set are accessibility for measurement, independence, monotonicity with preference, completeness of the set, and meaningfulness for feedback. Monotonicity, in this content, implies that an increase in the attribute levels are monotonic, a simplication is possible. Fisher (1972) and Gardiner (1974) note that a straight line approximation to the utility function results in minor losses of model accuracy. Independence implies that the value of an attribute is independent of changes in other attributes. Completeness has to do with prediction: if the attribute set is complete and the decision maker consistent, then all behavior should be accounted for.

Information costs may comprise attributes of special note. Often, the benefits of an information acquisition are simply weighted against the costs of acquiring the information. If a net gain is anticipated, acquisition of the information is considered justified. Often, though, the costs themselves are multi-dimensional, comprising energy costs, time delays, equipment expenditures, and risks of detection. The scaling, weighting, and aggregating of these costs may be most easily performed in combination with all of the non-cost attributes--tactical gains,

political impact, etc. Then, trade-offs among each of the factors may be performed in a single, consistent operation using the MAU model. If the cost-benefit formulation is used, on the other hand, the weighted aggregate of benefits is divided by the weighted aggregate of costs.

As a rule of thumb, five attributes appears to be an upper limit to the number of factors a decision maker can effectively consider (V. Winterfeldt, 1975). If several factors contribute to one consequence dimension, these factors should be combined using a single common scale--dollars, ship-equivalents, fuel quantity, etc.

Each of the attributes--communications costs, vehicle losses, etc.,--must be scaled with interval properties along a set range. The least desirable consequence that may occur is assigned a level of zero on the scale. The most desirable consequence is assigned a level of one. The weighting factors k_i should also be normalized so that the overall worst combination of factors results in a value of zero and the overall best combination a value of one.

If the cost-benefit formulation is used, the attributes must also have radio scale properties, since ratios are involved in the computations. To ensure ratio properties, the benefit attributes should be scaled with respect to a zero cost option.

<u>Determination of the Attribute Set</u>. The initial selection of attribute sets may be performed by interview, intuition, or analysis. Protocol analysis is a subjective interview technique whereby the operator introspectively recounts the factors and procedures which enter into his decisions. Consciously considered attributes may be identified from this introspection. A second, more objective technique is possible if the decision situation is highly defined. The feature set can be determined

according to the predictive error rate and from correlations of the candidate attributes (Felson, 1975). The first attribute chosen is that with the lowest expected probability of error (EPE). The EPE is the error rate that would result if the i^{th} attribute alone were used as a basis for decision making. The second feature chosen is the one with the smallest correlation with the first attribute. The choice of the i^{th} attribute depends on its correlation with the i-1 attributes already chosen.

The attributes in their raw form may be highly non-linear. Linear transformations to achieve interval scales are often warranted. The effect of the linear transformation is normally minor compared to the magnitudes of the test/retest reliability and intersubject differences (Edwards and Guttentag, 1975).

1.6 Parameter Estimation

The information value models exhibit a number of parameters which must be estimated: event probabilities, message characteristics, attribute levels, and attribute weights. Subjective or objective estimates must be made of each parameter.

Attribute Level Determination. The actual level of each of the attributes for a given outcome can be determined by mappings between predictive features and the attributes. Predictive features must be identified which are accessible to the information management program and capable of determining the consequence levels. Mappings between the predictive features and the attributes are either pre-established or determined by observation and adjustment.

Attribute Weight Estimation. The policy defining factors in the model, the importance weights k_i, are parameters suitable for either objective or subjective estimation. If the consequences can be defined along objective scales (dollars, ship-equivalents, etc.), then the weights could be derived by analysis and input prior to system operation. Unfortunately, Felson (1975) states that only in a few highly structured situations can such an optimal model be derived. More often, the operator's goal structure, expressed as importance weights, must be elicited or inferred and then incorporated in the model.

Off-Line Methods. The operator's subjective weights may be defined off-line by elicitation or on-line through inference. The off-line methods include direct elicitation of preference, decomposition of complex gambles into hypothetical lotteries, and use of multi-variate methods to analyze binary preference expressions. These techniques are accurate and reliable in many circumstances, but they have a number of disadvantages when applied to operational systems. Typically, these methods require two separate stages--assessment nad application. Assessment requires an interruption of the task and elicitation of responses to hypothetical choices. Problems arise with such procedures since the operator's judgments may not transfer to the actual situation; the decision maker may not be able to accurately verbalize his perference structure; and the judgments made in multi-dimensional choices are typically responses to non-generalizable extreme values.

The off-line, direct elicitation methods appear to be best suited for those situations where repetitive decisions are not available and extensive axiomatic tests of the decisions are necessary.

Unit Weighting Schemes. Unit weighting schemes (in which all weights k_i are set equal to 1.0) have been found to be quite effective in certain circumstances. Errors in the model form, positive correlations between

variables, and small sample sizes all reduce the predictive capabilities of differential weights compared to unit weights (Einhorn and Hogarth, 1975). Essentially, the more precise and parsimonious the model, the more important differential weights are.

Unit weighting schemes are expected to see only minor application in aiding advanced aircraft operations. Careful selection of attributes minimizes intercorrelations between variables, and the correlations that do occur should tend to be negative. For example, in most cases costly information is generally more informative than inexpensive information, and equipment attrition tends to be negatively correlated with goal attainment. These circumstances favor inferred weight models. Unit weighting schemes should primarily be useful as starting points for estimation, or as strategies for situations in which a great deal of noise is present.

Adaptive Weight Estimation. Estimation techniques relying on inference from in-task behavior are also often useful. The inference techniques can be based on non-parametric forms of pattern recognition. Here a model of decision behavior is assumed and the parameters of the model are then fitted by observation and adjustment. Briefly, the technique considers the decision maker to respond to the characteristics of the various alternatives as patterns, classifying them according to preference. A linear discriminant function is used to predict the decision maker's choices, and when amiss, is adjusted using error correcting procedures. In this way, no preference ratings or complex hypothetical judgments are required of the operator.

The adaptive nature of the estimation program derives from the error correcting adjustment mechanism. Expected consequence vectors associated with each information source are input to the model. These consequence

vectors are dotted with the weight vector, resulting in evaluations along a single utility scale. The maximum utility choice is determined and compared with the operator's actual choice. If a discrepancy occurs, the weight vector is adjusted according to the following rule:

$$\underline{k}' = \underline{k} + \lambda(\underline{x}_c - \underline{x}_m)$$

where $\underline{k}'$ is the updated weight vector, $\underline{k}$ is the previous weight vector, λ is an adjustment constant, $\underline{x}_c$ is the attribute vector of the chosen alternative, and $\underline{x}_m$ is the mean attribute vector of all alternatives ranked by the model above the chosen alternative.

Ideally, the error correction moves the weight vector in a direction minimizing subsequent errors. The amount of movement depends on λ, the adjustment increment. Similar techniques can be used for modeling the action decision.

1.7 System Performance Analysis

Performance Measures. The performance of a complex control and decision task is normally gauged using a combination of indices such as error rate, accuracy and speed. For simplicity in exploratory studies, it is possible to use error rate as a single figure of merit by assigning the outcomes to discrete categories and using a forced-paced presentation of constant length. Much of the work on which these guidelines are based used such a format.

Decision Aising. The aiding actually provided to the operator can be estimated in two ways:

(1) Increased system performance. The difference in overall system performance with and without aiding gives a measure of the system improvement. However, this performance gain does not reflect the unburdening provided by aiding.

(2) Unburdening. The unburdening of the operator may be seen by a change in secondary task performance with and without aiding. Problems develop with secondary tasks, though, since two independent performance measures result--one for the primary task and one for the secondary. The possible ambiguity can be lessened by the cross-adaptive technique of Kelley and Peterson (1969). Here, the primary task performance is kept at a stable criterion by varying the secondary task difficulty. The secondary task performance then indicates unburdening. Two alternative but less sensitive measures of unburdening are the reduction of operator control time and decrease in number of operator decisions found with aiding.

Decision Model Performance. The effectiveness of the decision model in inferring decision parameters and predicting operator behavior can be determined by a number of methods. Among these means of model validation are axiomatic tests, measures of prediction, construct validity tests, and checks of operator acceptance. Prediction is the simplest of these. The ability of the adaptive model (and of any other model) to predict behavior in both the information and control decisions can be determined directly. Construct validity tests are more difficult. These tests are made by comparing the inferred weights with weights estimated off-line by other techniques. The off-line estimation techniques may involve direct estimation, paired-comparisons, or interpolative techniques.

<u>Auxiliary Measures</u>. Additional measures of decision quality and decision stability should be used. The decision quality measures are determinations of the deviation from maximum expected utility exhibited by the operator. Assuming model accuracy, this is a measure of sub-optimality of behavior due to logical inconsistency. The second measure, decision stability, is measured by the overall amount of change of the estimated preference structure.

The deviation from expected utility can be computed using the following expressions.

$$DEU = \frac{1}{n} \sum_{i=1}^{n} \left\{ MAU\ (\text{model choice}_i) - MAU\ (\text{operator choice}_i) \right\}$$

In effect, this is a measure of the average "distance" between the predicted and actually chosen alternatives.

<u>Subjective Measures</u>. The attitude of operators toward their interaction with the computer aiding system can be examined in structured form by means of rating scales and in free form through voluntary comments and experimenter observations. Rating scale judgments should be taken after an experimental sequence is complete, rather than interrupting the continuity of the task with interim ratings. Scales that have been found to be useful are:

(1) Competition/Cooperation--To what extent was the interaction characterized by conflict?
(2) Aiding--How much unburdening did the machine provide?
(3) Relative Effectiveness--What are your estimates of the machine's and your own quality of performance?

(4) Automation Predictability--What proportion of the information and control recommendations were expected?

(5) Satisfaction--How satisfied were you with your own and with the machine's performance?

1.8 Information Feedback

Information Choice. The selection of the type of information for display may be indicated using a variety of means. Among these are:

(1) Signal Light. A discrete light may be used to signal the recommended choice on a bank of switches. This is well suited to situations where manual overrides are frequent, since the control response is easily made.

(2) Graphic Legend. A textual display of the choice on the CRT appears best suited to fully automated information management. The information sensor characteristics can be shown along with the information itself.

(3) Auditory Signal. An auditory alerting signal may be called for if information transfers are infrequent and must be attended to immediately, e.g., fault displays.

Level of Confidence. An estimate of the expected effectiveness of the information management program in the immediate situation is essential. Two types of feedback are possible:

(1) The marginal benefit of a given information choice over the remaining choices. This gives some ideas as to the strength of the choice.

(2) The confidence associated with the information evaluation. This is dependent on the experience associated with the particular set of estimating conditions.

Decision Policy Feedback. For training purposes, it is useful to display the estimated policy weights back to the operator while the task is being performed. Such policy feedback was found to be more effective as a training tool than the simple display of the decision outcome (Slovick, Fischhoff, and Lichtenstein, 1977). Display of the policy criteria also puts the operator more intimately in contact with the operation of the information management system. Operator acceptance of aiding tends to be higher when the operator's values are seen to be incorporated in the systems decisions.

A second form of feedback deals with operator's decision consistencey. The DEU measure can be used to evaluate decision consistency, as can a comparison of strategies between the information seeking and subsequent control decision.

Human/Machine Communication. The operator-to-machine comprises all of the control actions, parameter inputs, and information requests made by the operator. These should include:

(1) Direct Manual Control. Manual inputs for input of the decision situation, selection of information sources, and execution of control actions must be provided in the same manner as in non-automated systems.

(2) Inputs to Automated Information Management Program. Provision must be made for transmitting situational conditions, decision parameters, confidence thresholds and other task descriptions by keyboard or other input device.

(3) Overrides of Automated Information Selection Decisions. A simple control such as a momentary push-button is necessary for rejecting machine decisions.

(4) Information Requests. Queries concerning the sensor environment or program state should be permitted by keyboard or other means.